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Scope and Method of Study: From a review and correlation of pertinent literature on electro-osmosis, a qualitative examination is presented in this report, of the theory and application of electro-osmosis as utilized in the field of soil mechanics.

Findings and Conclusions: Electro-osmosis controls the flow of soil moisture and favorably alters some of the engineering properties of soils. The improvement of these properties is of a temporary nature when produced by electro-osmosis alone, and of a permanent nature when produced by electro-osmosis in conjunction with certain chemical processes. Electro-osmosis is successfully applied in overcoming difficulties in construction projects which involve soft, saturated clays and silts. Estimation of the costs of employing the process is complicated by variations in the physicochemical properties of the soil-water system. Economic justification for employment of the process is therefore largely dependent upon the judgment of the engineer.

ADVISER'S APPROVAL _____

ELECTRO-OSMOTIC EFFECTS ON SOILS

By

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PREFACE

Electro-osmosis in soils controls the flow of soil moisture and alters some of the engineering properties, by application of an electric current. It is applied in overcoming difficulties in construction projects which involve soft, saturated clays and silts. Although the principle of electro-osmosis was discovered as early as 1808, it was not until around 1930 when Dr. Leo Casagrande began experiments in applying the phenomenon to soils that a beginning was made toward practical utilization of the process by the engineering profession.

It is the purpose of this report to gain an understanding of the effects of electro-osmosis as applied in the field of soil mechanics. Toward that end, the pertinent literature on the subject has been reviewed and correlated. The complexities of soil as an engineering material are of such number and magnitude, that a quantitative study of electro-osmotic effects would be extremely unwieldy, if possible at all. Therefore the scope of this paper is limited to a qualitative sense, and mathematical treatments are presented only in those instances where application to actual soil conditions appears justified.

Grateful acknowledgement is given to Professor J. V. Parcher for his valuable counsel and review of this study, and for his kind consideration in the loan of reference material. The encouragement and advice of Professor P. G. Manke are greatly appreciated. Thanks are also extended to Mary Jane Walters for careful, accurate typing of this report.

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CHAPTER I
INTRODUCTION

Increased importance has been given within recent years to the development of practical methods of stabilizing fine grained soils by removal of excess moisture or by chemical treatment of the material in place. Previous to this, the knowledge of the physicochemical nature of soils was incomplete to the extent of being an obstacle to this development. The rapid advancements made in the field of soil mechanics, however, and the improvement of the analysis of physicochemical properties, crystalline structure and mineralogical constituents have opened a new era in soil mechanics.

Two techniques developed to stabilize fine-grained soils are electro-osmosis and electrochemical stabilization. These processes produce a movement of liquid through a porous material under the influence of an electro-osmotic force. In engineering practice electro-osmosis or electrochemical stabilization is applied to such soils as silt, sandy silt, loess, sandy clay and clay. It has been used to overcome difficulties in excavation and soil stabilization when the high retention forces of the water film surrounding soil particles, and the low permeability of the soil render the usual mechanical or hydraulic methods unsatisfactory.

This report gives an explanation of the manner in which the physicochemical properties of the soil-water system affect the mechanism of the electro-osmotic and electro-chemical processes. Accordingly,

emphasis is placed on the nature of the double layer, the manner in which it is formed, and the factors which affect it. The mechanism of electro-osmosis is discussed and its effects on consolidation and stabilization are examined. Significant results of laboratory studies on electro-osmosis by several investigators are cited. Practical applications of electro-osmosis are reviewed to illustrate the manner and extent to which the process has been successfully utilized.

CHAPTER II
PHYSICOCHEMICAL PROPERTIES OF SOILS

Soil as a Colloidal System

According to Hauser⁽¹⁾ and others, a material on which the influence of surface charges is predominant when compared to the influence of gravity, is said to be in the colloidal state. Therefore, finely sized soil particles surrounded by moisture films can be considered as a colloidal system. A colloidal system differs from a true solution in that the molecules are not homogeneously mixed. A colloidal system is a multi-phase system in which the dispersed or internal phase is analagous to the solute of a true solution, and the dispersing medium or external phase is analagous to the solvent of a true solution. The dispersed phase of a colloidal system is not truly soluble in the dispersing medium. Instead, the dispersed phase exists as very finely divided particles which remain suspended in the dispersing medium. Thus, the soil particles form a dispersed phase and the water in which they are distributed constitutes the dispersing medium.

Charge on a Colloidal Granule

Hartman⁽²⁾ reviews Debye's theory that a solid tends to pass from the atomic to the ionic state, i.e., pass into solution, when brought into contact with a liquid. This tendency, designated as the electrolytic solution tension, is a property inherent in the solid and

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is a constant. As ions of appropriate charge, produced by the electrolytic solution tension, leave the solid an opposite charge appears on the solid itself. This charge exerts an electrostatic attractive force on the dissolved ions and opposes the transformation from the atomic to the ionic state. In addition, the osmotic pressure of the solution surrounding the particle tends to replace the removed ions with those already in solution. These two factors opposing the electrolytic solution tension, tend to reduce the magnitude of the charge on the particle itself, or even to cause the particle to acquire a reverse charge.

Following Coulomb's law of attraction and repulsion, the charge attributed to the colloidal particle itself, attracts from the suspending medium an equal but opposite charge thereby making up a colloidal granule. Hence, if a particle is positively charged it will attract negative charges from the solution and the resulting granule will behave in a manner equivalent to that of an anion.

Hartman⁽²⁾ attributes the first explanation of the nature of the electrostatic charge on a granule to Freundlich. He suggests that colloidal particles in solution have the property of adsorbing ions of a definite charge. Consequently, the selective adsorption properties of the suspended particle determine the sign of the charge. If cations are adsorbed to a greater extent than are anions, the charge will be positive. If anions are selectively adsorbed the charge will be negative.

When a colloidal particle is suspended in a liquid of low ion content, ion adsorption by the particle is extremely small and may be entirely absent. Therefore, the charge on the colloidal particle approaches a minimum. Pure water, which has no foreign ions present, possesses a definite dissociating power and is in itself slightly dissociated. The

colloidal particle may then selectively adsorb hydrogen or hydroxyl ions and become positively or negatively charged respectively.

Structure and Polarity of Water Molecules

Debye⁽³⁾ states that a molecule may be represented as a system of electrical charges. The term "polarity," expresses the molecular properties associated with the actual arrangement of the electrical charges. The polar structure of water molecules results from the non-symmetrical distribution of electrical charges in the individual atoms which comprise the molecule. Therefore, in a certain region of the molecule there is an excess of positive charge while in another region there is an excess of negative charge. The positive and negative poles thus formed constitute a dipole, and the dipole moment is obtained by multiplying the electrical charges at the electrical centers by the distance between these centers.

The polarity of a water molecule is illustrated in figure 1 by a triangular arrangement of atoms.

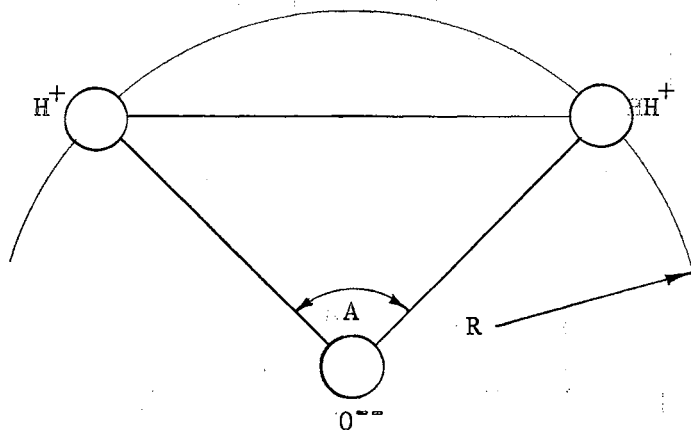


Figure 1. Triangular Model of a Polar Water Molecule

The hydrogen ions are located in a shell of radius R which is concentric about the oxygen ion. The angle A is reported as having a magnitude of about 104° to 110° depending on the assumptions made in the calculations⁽⁴⁾.

Figure 2 illustrates the concept of attraction of dipolar water molecules by a negative ion. In the case of a positive ion the orientation and attraction is the reverse of that indicated.

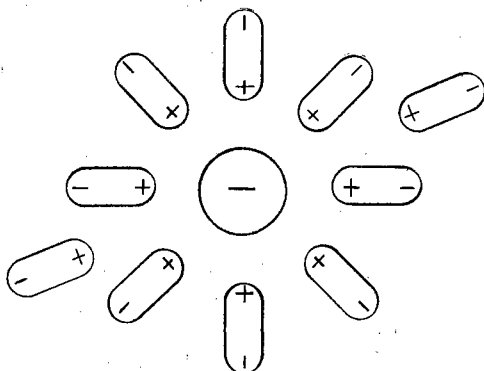


Figure 2. Orientation and Attraction of Dipolar Water Molecules

A mutual electrostatic interaction of water molecules results from the presence of electrical charges in the polar water molecules. The positive pole of one molecule is therefore attracted to the negative pole of another water molecule. Debye⁽³⁾ illustrates that in addition to the electrostatic forces, the interaction of dipoles is affected by the van der Waal's forces of universal attraction. Figure 3 illustrates the effect of van der Waal's forces.

In position A the main effect is repulsion, from the orientation of like charges. The field strength displaces the negative charges toward the positive charges. Therefore, the distance d between the electrical centers, which is the moment arm of the dipole, is shortened

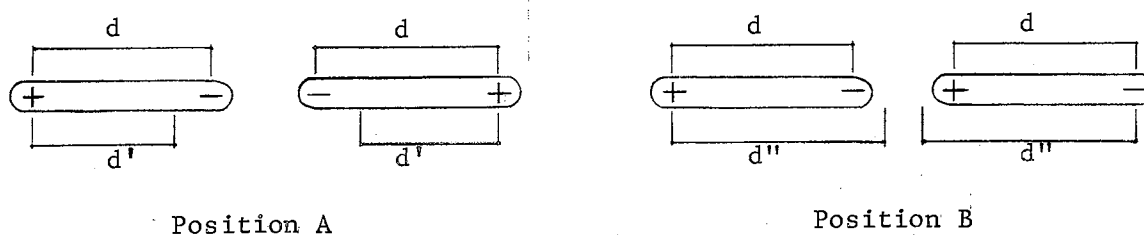


Figure 3. . Effect of van der Waal's Forces

to distance d' . Consequently the dipole moment of each molecule is reduced and the repulsion between the molecules decreases; in other words, an attractive force appears as a secondary effect. In position B the main effect is attraction. In this case the field strength displaces the charges so that the dipole moments increase. Therefore, an attractive force again appears as a secondary effect.

Basic Concepts in Double Layer Formation

The fundamental concepts in the formation of an electrical double layer are illustrated by a model consisting of a box containing a simple solution in which ions are uniformly distributed. If one of the walls of the box becomes charged, while an equivalent number of unlike ions are added to the solution to maintain electro-neutrality, the new distribution of ions is then subject to examination. Here the wall of the box is analagous to an interface or boundary between the internal and external phases of a colloidal system. In general the ions opposite in charge to that of the wall, termed counterions, will be attracted to the wall and the like ions repelled, while thermal motion will tend to distribute both uniformly throughout.

If thermal motion were not present, an equivalent amount of counterions would be attracted by the wall and cover it, exactly neutralizing its charge. A situation similar to the absence of thermal motion may occur if electrostatic forces of attraction are so strong, or so reinforced by van der Waal's forces, that they overcome the forces due to thermal agitation. An electrical double layer has thus been formed which consists of the charges at the boundary of the wall and the neutralizing counterions. The electric potential of the double layer is zero since the charges of the wall have been balanced by those of the counterions. Therefore, the remaining ions in solution are not affected further by the presence of the double layer.

If sufficient thermal motion is present, the formation of a compact double layer is prevented. Neglecting the effects on the like charged ions, thermal agitation of counterions is such that they tend to concentrate only near the charged wall rather than on it. Only if the kinetic energy of the counterions is completely overcome can the entire charge of the wall be neutralized directly at its surface. In addition the counterions near the wall screen those further away, from the full charge of the wall so that the concentration of counterions and the resultant electric field intensity decrease with distance from the wall.

If the effect on the counterions is neglected, the effect on the like charged ions will be the opposite of that described. The like ions will be repelled by the wall and the removal of a like ion has the same effect as the addition of a counterion in screening the charge on the wall. Hence, the reduction in concentration of like charged ions also results in a decrease of potential and electric field intensity with distance from the wall.

The Helmholtz Double Layer

Hauser⁽⁵⁾ attributes the first concept of the electrical double layer to Quincke, and Preece⁽⁶⁾ credits the first mathematical treatment to Helmholtz. Helmholtz takes as a model of the double layer the simplest concept of charge, in which a plane of uniform charge is separated at some distance from a plane of opposite charge. He considers the distance between the two electrical layers to be equal to the diameter of one molecule, thus forming a molecular condenser. Helmholtz⁽⁷⁾ describes the double layer as follows: "The liquid is galvanically opposite to the wall of the vessel and the two form an electric double layer along their boundary surface This layer has an extraordinarily small but not disappearing thickness. The side of the layer adjacent to the boundary surface clings immovably to the wall (at least in the cases to which the experimentally found rules relate); the rest is movable but subject to the internal friction of the liquid."

As previously noted, the separation of charges at an interface gives rise to an electric potential difference or a potential gradient. According to Helmholtz, the gradient of this potential drop is sharp and varies linearly with distance. The electric potential at any point within the double layer is termed the zeta potential because of the symbol commonly used in its representation. This is distinguished from the magnitude of the total or thermo-dynamic potential drop across the double layer. The arrangement of ions in the formation of a Helmholtz double layer and the linear relation of the potential are shown in figure 4.

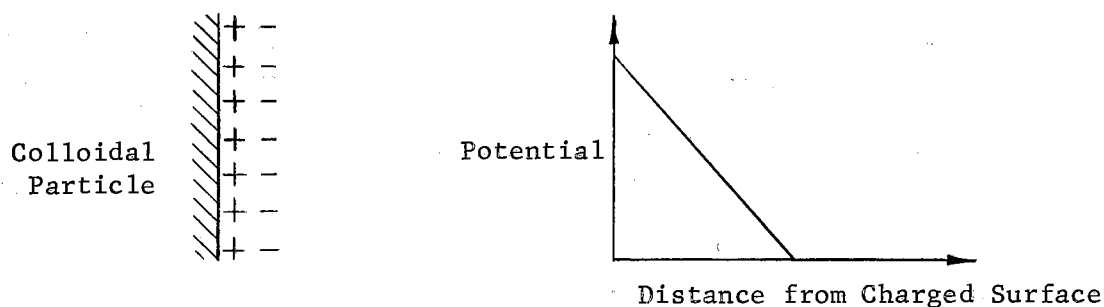


Figure 4. The Helmholtz Double Layer

The Gouy-Chapman Double Layer

The first concept of a diffuse double layer to account for the thermal motion of ions is credited to Gouy and Chapman independently⁽⁸⁾. Gouy shows that the ions of the double layer cannot be concentrated within a definite distance from the interface because there must be an equilibrium between the electrical forces causing the existence of the double layer and the forces which tend to maintain homogeneity. The diffuse double layer after Gouy and Chapman consists of excess ions present on the solid phase and an equal amount of ionic charge of opposite sign distributed in the solution phase near the interface. The charge on the solid is considered to be uniformly distributed and the space charges in solution are treated as an unequal distribution of point-like ions, the dimensions of the ions being neglected. The distribution of ions in solution is calculated by means of the Boltzmann relation expressing that at places of positive potential the negative ions are concentrated while for places of negative potential the opposite occurs. Hence, the concentration of the electrical charges decreases from the interface according to an exponential law rather than linearly as described by Helmholtz. Rutgers⁽⁹⁾ points out that the thickness of the double layer is on the

order of 10^{-6} or 10^{-7} cm. The ion distribution and the variation of the potential are shown in figure 5.

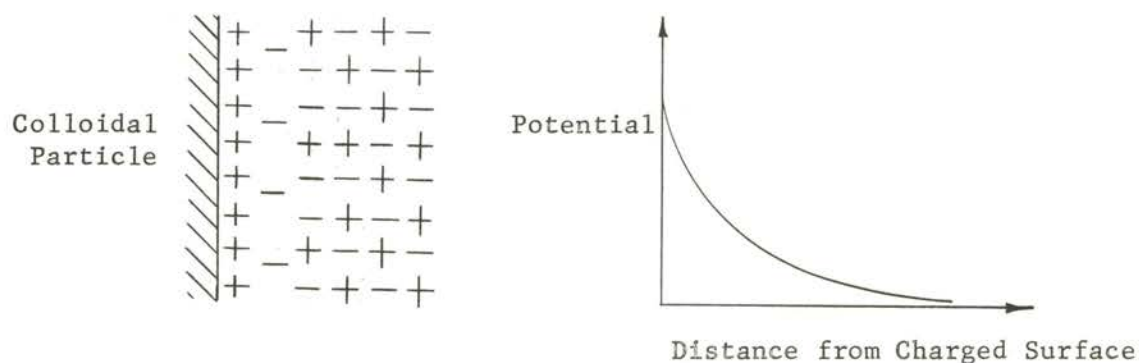


Figure 5. The Gouy-Chapman Double Layer

The Stern Double Layer

An additional refinement in the concept of the double layer is credited to Stern⁽¹⁰⁾. He considers the possibility of specific adsorption of ions and assumes that ions so affected are located within a distance δ from the interface. Hence, a division of the double layer by Stern is on the basis that the charges in the outer movable layer are affected by thermal and electrostatic forces only, whereas those in the inner layer are affected also by the forces of selective adsorption. Immediately adjacent to the surface then, there exists a layer which is fixed on the surface of the solid and is approximately one ion in thickness, which is the value of δ . This layer is considered practically immobile and displays a linear potential drop as in the Helmholtz layer. Adjacent to this single ion layer there is a second part of Stern's double layer which is diffuse in character. This portion of the double layer corresponds to the Gouy-Chapman double layer. Therefore, Stern's concept is a combination of the Helmholtz and Gouy-Chapman double layers. The

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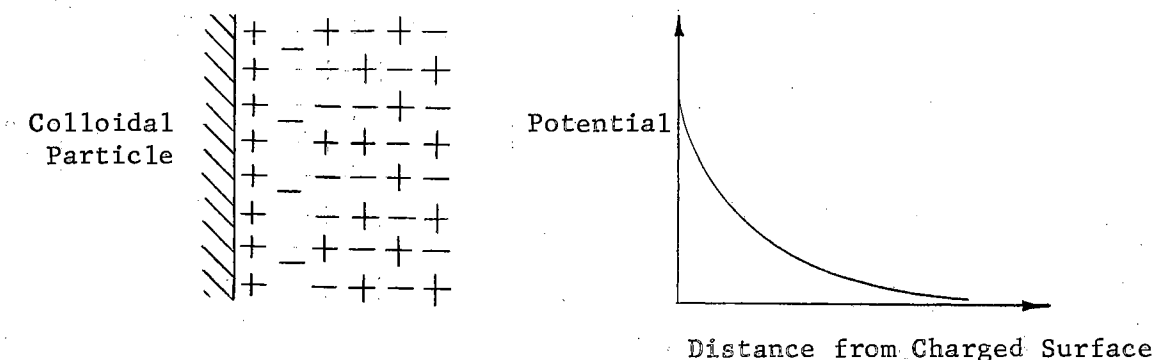


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ion distribution and the variation of the potential are illustrated in figure 6.

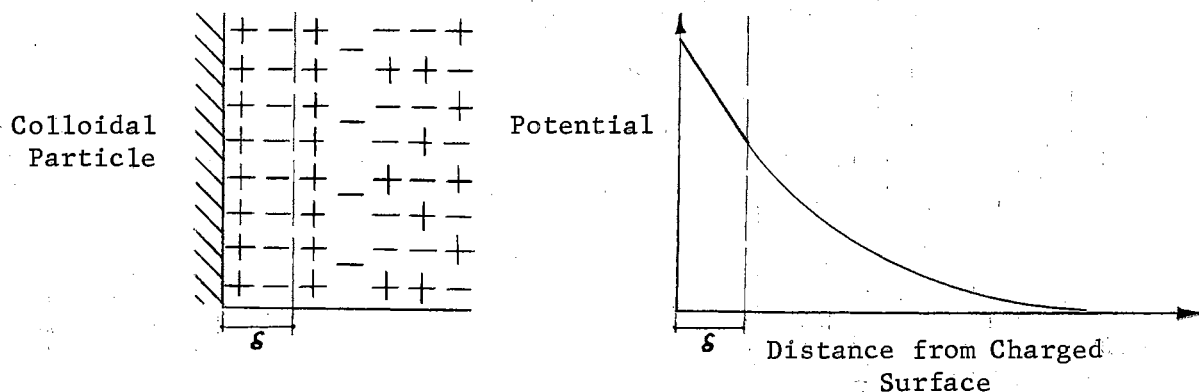


Figure 6. The Stern Double Layer

The Effect of Electrolytes on the Zeta Potential

Hartman⁽²⁾ points out that the value of the zeta potential is greatly influenced by adsorption of ions at the interface since the nature of the double layer is thereby affected. Von Buzágh⁽¹¹⁾ also states that changes occur in the electrical double layer if a system is treated with foreign electrolytes in increasing concentrations. Ionic substitution takes place in various ways according to the nature and quantity of the ions originally present in the double layer and those added afterwards. If the concentration of ions in the dispersing medium is increased while the potential remains unchanged, a corresponding and proportional increase in concentration of counterions occurs in the vicinity of the diffuse side of the interface. If the concentration is made strong enough, the zeta potential may be reduced to zero or even reversed. This may be due to neutralization of the charge on the particle or to such a decrease in the thickness of the double layer that it eventually collapses and reforms with the charges reversed. The screening effect of a doubly charged

particle is equivalent to that of two singly charged particles. Hence, the higher the valence of the added ions, the greater the reduction in zeta potential.

Space Lattice and Base Exchange

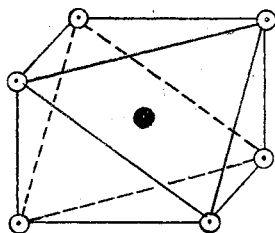
The following discussion is based on that given by Preece⁽⁶⁾. Ions or molecules when combined to form a crystalline solid are grouped in that geometrical arrangement which results in the greatest possible degree of electrical neutralization or balance of electrostatic forces within the structure. The most elementary grouping of this sort is termed a unit cell. The silicon-oxygen tetrahedron and the aluminum-hydroxyl octahedron shown in figure 7 are typical covalent unit cells and are the principal constituents of the lattices of various clay minerals.

○ OH -3

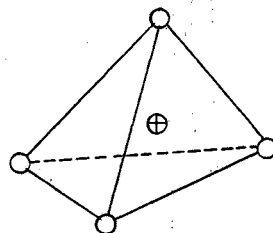
○ O -2

● Al +3

⊕ Si +4



Aluminum-Hydroxyl
Octahedron



Silicon-Oxygen
Tetrahedron

Figure 7. Unit Cells

If a cell is electrically unbalanced it will tend to establish a bond with any other compatible ion within its field of attraction. Each oxygen atom of the silicon-oxygen tetrahedron, for example, has an unsatisfied negative valence. In the formation of elementary lattice structures such as the gibbsite sheet by aluminum-hydroxyl octahedrons, the valences may be balanced within the sheet but unsatisfied at the surfaces, edges or corners of the particle formed. If such a particle is suspended in a solution so that there are adequate ions available, double layers will be formed wherever there are unsaturated valences. This may occur on the interfaces between stacked lattice sheets as well as on the overall outer surface, depending on the bond between the lattice sheets. If the bond is strong no water can enter between the sheets and hence no double layer can form. When a solution is replaced by one containing entirely different ions, the new ions may replace the ions of the original double layer, either in whole or in part, if it will result in a decrease in the degree of hydration or in a lower net charge. This process is called base exchange.

Base exchange may also occur within the lattice structure, such as in the replacement of the aluminum or silicon atoms in the montmorillonite and illite lattices, but quantitatively this is relatively unimportant with respect to base exchange capacity. The base exchange capacity of important soil types and the significant type of exchange external to the lattice are summarized in table I.

TABLE I

TYPE OF EXTERNAL BASE EXCHANGE AND BASE EXCHANGE CAPACITY

Soil Type	Type of External Exchange	Capacity (Milli-equivalents per 100g)
Kaolinite	at the edge surface only	3-15
Illite	at the overall outer surface only	20-40
Montmorillonite	at the outer surface and the interfaces	60-100

CHAPTER III

ELECTROKINETIC EFFECTS

Electro-Osmosis

The term electro-osmosis is used to describe the electrokinetic phenomenon of liquid moving through a porous medium under the influence of an externally applied electrical field. The derivation of this term is based on an analogy of the flow of fluid through a permeable membrane due to differences in concentration, which is osmosis. Despite the similarity in names the two processes are completely different, unrelated phenomena.

Jumikis⁽⁴⁾ has reviewed the historical background of the development of electro-osmosis. The phenomenon of electro-osmosis was discovered by Reuss in 1808, but he did not explain it. Wiedeman performed systematic research on electro-osmosis in 1852. In 1859 and 1860 Quinke made quantitative measurements at a single capillary and related the converse phenomenon of streaming potential to electro-osmosis. Helmholtz, in 1879, formulated Quinke's theory in mathematical form. Smoluchowski and others slightly modified Helmholtz's mathematical formulation, but the quantitative results remain substantially unchanged.

Under the application of an external electric field produced by direct current, the positive charges (cations) in the diffuse double layer are attracted by the negative electrode (cathode) and thus tend to be translocated, while the negatively charged ions (anions) tend to move toward the positive electrode (anode). The ions of the diffuse double

layer drag with them oriented water molecules, thereby setting the diffuse portion of the double layer into motion. The direction of motion depends on the sign of the predominant ionic concentration in the diffuse layer. The movement of the liquid takes place against the liquid adhering firmly to the surface of the solid and not against the solid surface directly. The motion is therefore resisted by the viscosity of the water. If a double layer exists around the inner surface of a capillary tube filled with water, the cylinder of free water enclosed by the double layer will move along with it. This is illustrated in figure 8.

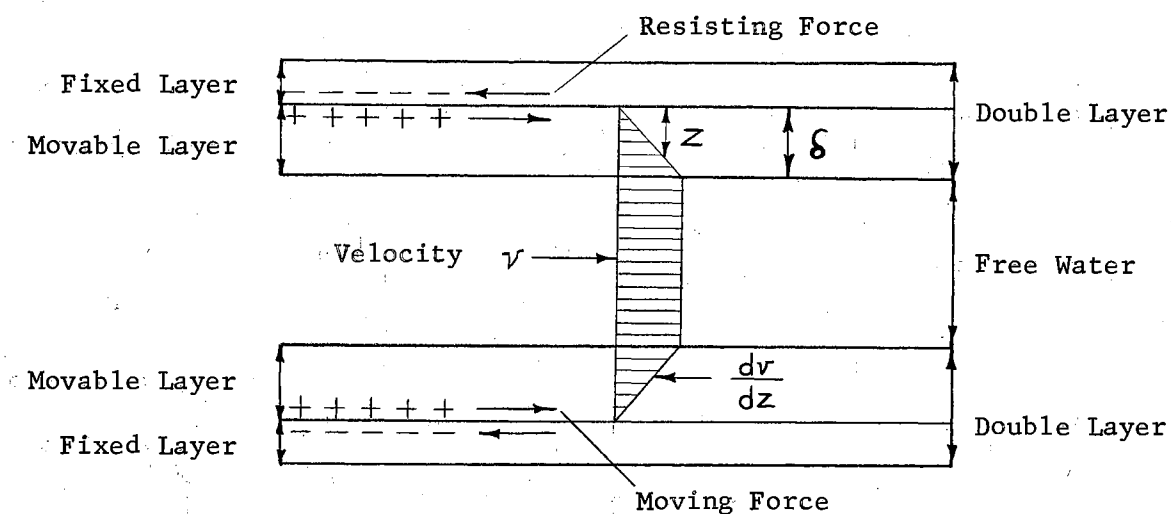


Figure 8. Electro-Osmotic Flow in a Capillary

Rate of Electro-Osmotic Flow

The development of the equation for quantity of electro-osmotic flow per unit time is based on the Helmholtz derivation as outline by Freundlich⁽¹²⁾.

$$v = \frac{V}{\pi r^2} \quad (1)$$

where v = average velocity of flow in a capillary

V = volume of liquid moved per unit time

r = radius of the capillary

According to Newton's law of viscosity⁽¹³⁾, the shearing stress

$$\tau = \eta \frac{dv}{dz} \quad (2)$$

where z is distance from the capillary wall and η is the viscosity of the fluid. Since the shearing stress is equal to a shearing force F over an area A , equation (2) may be written as

$$F = \eta A \frac{dv}{dz} \quad (3)$$

which for a unit area and a velocity gradient $\frac{dv}{dz} = \frac{v}{\delta}$, since δ is very small, becomes

$$F = \eta \frac{v}{\delta} \quad (4)$$

substituting v from (1), the force in the capillary tube then becomes

$$F = \frac{\eta V}{\pi r^2 \delta} \quad (5)$$

The force on a unit surface area produced by an externally applied voltage E , with potential gradient H , is equal to the product of the charge e on this unit surface and the potential gradient H , hence equating this to the shearing force,

$$eH = F = \frac{\eta V}{\pi r^2 \delta}$$

or

$$e = \frac{\eta V}{\pi r^2 \delta H} \quad (6)$$

If the double layer is regarded as a capacitor of potential ζ with a dielectric between the two layers of constant D , then according to Pender (14), for a capacitor of unit plate surface

$$\zeta = \frac{4\pi\delta e}{D}$$

or

$$e = \frac{\zeta D}{4\pi\delta} \quad (7)$$

equating (6) and (7)

$$\frac{\eta V}{\pi r^2 \delta H} = \frac{\zeta D}{4\pi\delta}$$

$$V = \frac{\zeta D r^2 H}{4\eta}$$

or

$$V = \frac{\zeta D r^2 E}{4\eta l} \quad (8)$$

where l is the distance between electrodes.

In the case of flow through a group of capillaries, the value r^2 is replaced by A_p , representing the cross-sectional area of the pores, hence equation (8) becomes

$$V = \frac{A_p \zeta E D}{4\pi\eta l} \quad (9)$$

Since $E = IR$ and $R = \frac{l}{A_p \lambda}$ where λ is the specific conductivity of the liquid, equation (9) becomes

$$V = \frac{\zeta I D}{4\pi\eta \lambda} \quad (10)$$

If the current I is kept constant, equation (10) shows that the

flow of liquid per unit time does not depend on either the length or the area of the capillaries. Thus there exists a significant difference between electro-osmotic and hydraulic flow through porous systems, since the hydraulic flow rate is well known to depend on the area of the capillaries. Casagrande⁽¹⁵⁾ confirmed the results of this equation on many soils of varying hydraulic permeability, ranging in type from sands to fat clays, and concluded that a coefficient of permeability for electro-osmotic flow (K_e), is essentially independent of the pore size of the soils i.e., about of the same magnitude for sands, silts or clays provided that the zeta potential is the same for the major portion of the mineral matter in these soils. For all practical purposes the value of K_e may be taken as $.5 \times 10^{-4}$ cm. per sec. for a gradient of one volt per cm.

If the factors other than ζ are constant in equation (10), it is apparent that the rate of flow depends entirely on the magnitude of the zeta potential. If the double layer is collapsed, the zeta potential will be zero and the flow will stop. If the sign of the diffuse layer is reversed, the sign of the zeta potential will be reversed also, and flow will occur in an opposite direction.

Electro-Osmotic Pressure Head and Streaming Potential

If flow from a tube is prevented, a pressure head will be developed which will be equal and opposite to the force producing the flow. By assuming that Poiseuille's law applies to the movement of a liquid in a capillary, Freundlich⁽¹²⁾ has developed an expression for the pressure head of a single capillary

$$P = \frac{2\zeta ED}{\pi r^2} \quad (11)$$

Vey⁽¹⁶⁾ applies this expression to obtain a similar equation for a group of equal sized capillaries

$$P = \frac{2(1+e_0)S ED}{\pi^2 e r^2} \quad (12)$$

in which e_0 = initial void ratio

e = void ratio corresponding to D

Since non-uniform capillaries exist in soil, equation (12) does not give exact quantitative results. Assuming, however, that the soil grains undergo no major disturbance during a reduction in the void ratio, the relation of pressure to void ratio under a constant electromotive force should follow a fairly uniform pattern if there are no sudden changes in the value of S or D .

Vey demonstrated the validity of this assumption in a test of pressure on a fine grained sample. The relationship between electro-osmotic pressure and void ratio is shown in figure 9.

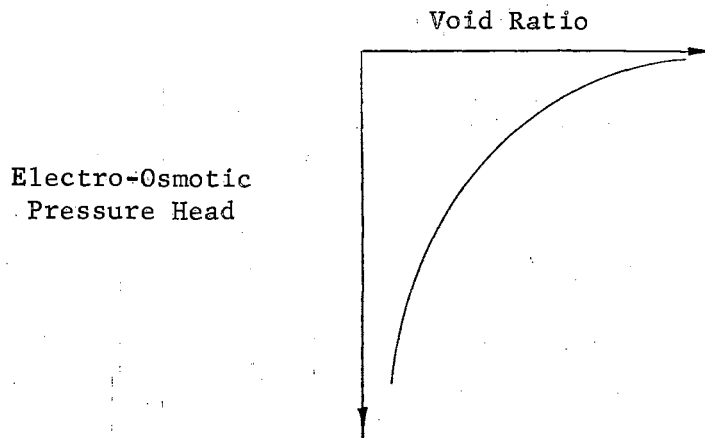


Figure 9. Void Ratio vs. Electro-Osmotic Pressure Head

If the action in the capillary were the reverse of that described, i.e., if the water were forced through the capillary by a pressure P ,

a difference of potential would be produced between two points in the stream of water. This potential difference is referred to as the streaming potential. Freundlich⁽¹²⁾ gives the Helmholtz expression for streaming potential

$$E = \frac{P \rho_0}{4 \pi \eta \lambda} \quad (13)$$

Since the value E is relatively easy to obtain by direct measurement, equation (13) affords a means of determining the value of the zeta potential, which otherwise is difficult to measure.

Consolidation and Stabilization

Since the electro-osmotic pressure head has the effect of increasing the pressure of the water in the pores of soil, Vey⁽¹⁶⁾ considers that it acts in the same manner as an applied load and may be considered simply as an additional consolidation load. He further considers that an electro-osmotic pressure P_0 will act in advance of pressure P_1 due to an applied load, during the process of consolidation. This is illustrated in figure 10.

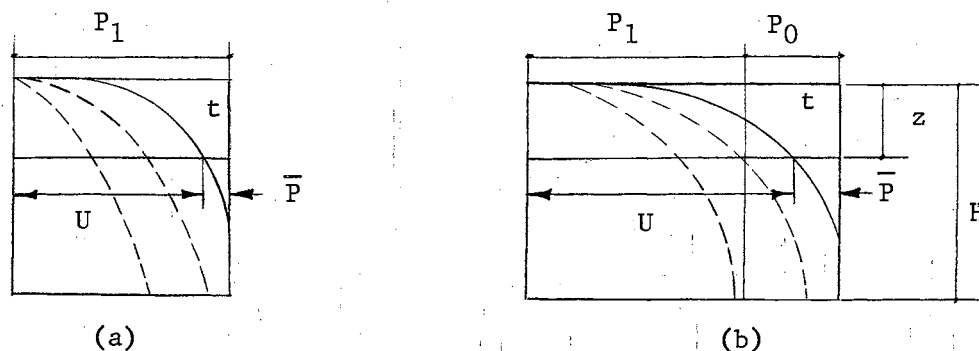


Figure 10. Isochrones in Consolidation

- (a) Under Load Only
- (b) Under Load and Electro-Osmosis

The isochrones at time t divide the areas of pressure such that

$$U = P_1 - \bar{P} \quad \text{in figure 10(a)}$$

$$U = (P_0 + P_1) - \bar{P} \quad \text{in figure 10(b)}$$

where \bar{P} is the intergranular pressure and U is the pore water pressure which at time t and depth z has not been transferred to the soil structure. As time t increases toward infinity, the pore water pressures approach zero in each case. Hence the final value of effective stress is greater for consolidation by load and electro-osmotic pressure than by load alone. From the shape of the isochrones it is indicated that P_0 originates at the top and progresses downward. Thus electro-osmotic pressure is considered to cause nearly all of the early consolidation, and to continue to act until the consolidation has progressed so that $\bar{P} = P_0$.

The actual process of consolidation is more complex than that illustrated thus far, and is in fact not completely understood. Casagrande⁽¹⁵⁾ considers that if there is no supply of water at an anode, a concave meniscus will be formed in a microscopic compressible capillary due to the electro-osmotic forces which tend to move the water to the cathode. Hence, a shortening or consolidation of the tube near the anode takes place because of compressive forces induced by the meniscus. A short distance further along the capillary there is a pressure due to accumulation of water which induces tension in the tube thus causing it to lengthen. At still greater distance from the anode there may be a substantial section of the tube which is unchanged in length. Finally, water in the vicinity of the cathode is subjected to large tensile stress due to the strong forces of attraction toward that electrode. This situation is pictured in figure 11.

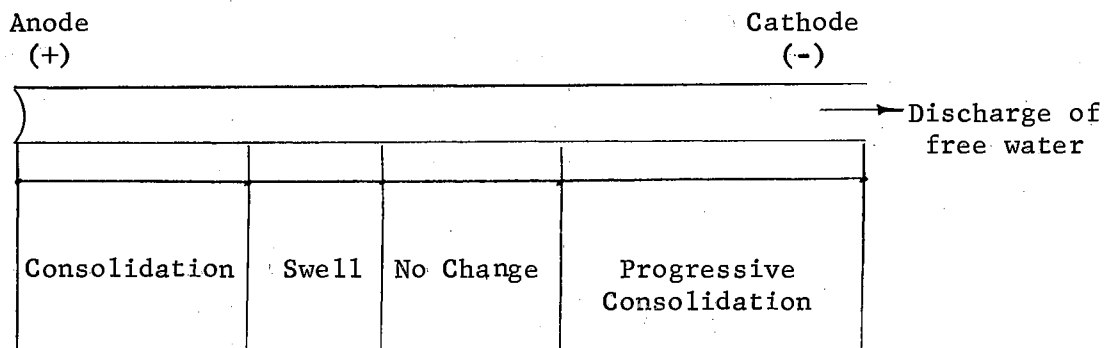


Figure 11. Consolidation in a Microscopic Capillary

Because of the tensile stress in the water near the cathode, dissolved gases can readily come out of solution to form bubbles in the capillary. Once such a bubble is formed, consolidation of substantial magnitude will take place in the tube between the cathode and the near side of the bubble which acts as a meniscus. The section of the tube actually enclosing the bubble is subjected to induced tension and may fissure or crack. As the gas escapes through the fissure water flows into the space of the bubble, thereby creating sufficient tension a short distance closer to the anode to cause formation of another bubble where the process is repeated. Thus a progressive consolidation moves from the cathode toward the anode over that distance in which sufficient tension can be created to form bubbles. The repeated development of fissures is considered the cause of the laminated structure, particularly in the vicinity of the cathode, of a clay which has been subjected to electro-osmosis.

Stabilization by electro-osmosis is accomplished in several

ways. The reduction of water content is a significant factor in any fine grained soil possessing some cohesive properties. The tensions developed in the pore water are achieved sooner in the case of silt than in clay because of the difference in hydraulic permeability. Pore water tension increases the effective stress between the soil particles and has the effect of increasing the internal frictional resistance. The increase in stability obtained by electro-osmosis alone is of a temporary nature in that the effects are lost after application of the current is discontinued; water begins to flow back into the soil, pore water tension reverts to pore water pressure, and the effective stresses are reduced which has the effect of decreasing the internal frictional resistance.

Electro-chemical stabilization embodies all the properties of electro-osmosis thus far presented, but in addition, it has the property of producing a permanent stabilization of the soil. The process may follow two methods. In the first method a chemical solution or mixture of solutions is applied to the soil through a hollow, perforated electrode and passes into the soil through electro-osmotic flow, which causes base exchange and other cementing reactions to occur. In the second method, stabilization of a permanent nature may be obtained without the use of chemicals if the soil responds to ions removed from the electrodes during electro-osmosis. Casagrande⁽¹⁵⁾ patented a method of electro-chemical stabilization by means of aluminum electrodes and also by the introduction of aluminum compounds at the location of the electrodes. He considers the resultant increase in strength of the soil to be due to drainage by electro-osmosis, base exchange, and deposition of aluminates in the pores by the soil. It is considered that aluminum ions have a tendency to react with available salts and thus form the cementing aluminates. The

hydrogen ions which are released at the anode, and which may travel through colloidal voids, are available for base exchange in the clay.

CHAPTER IV
LABORATORY INVESTIGATIONS

Reduction in Water Content

Casagrande⁽¹⁷⁾ reports on the results of laboratory tests conducted on remolded soils to determine the effect of electro-osmosis on the flow of water. The apparatus used in investigating parallel flow is diagrammatically shown in figure 12. It had no cover, and wire gauze or plates were used as electrodes on both ends. Flow was measured at the outlet or overflow.

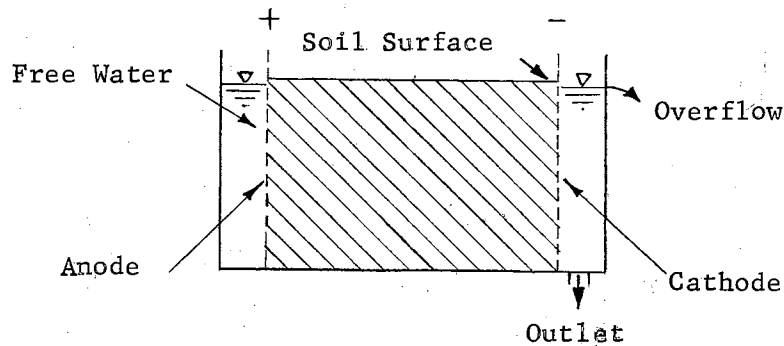


Figure 12. Apparatus for Investigating Parallel Flow⁽¹⁷⁾

Direct current with a voltage up to 225 volts was available to maintain potential gradients which varied from 0.1 to 12 volts per cm. The results for the flow soon after switching on the current are shown in figure 13.

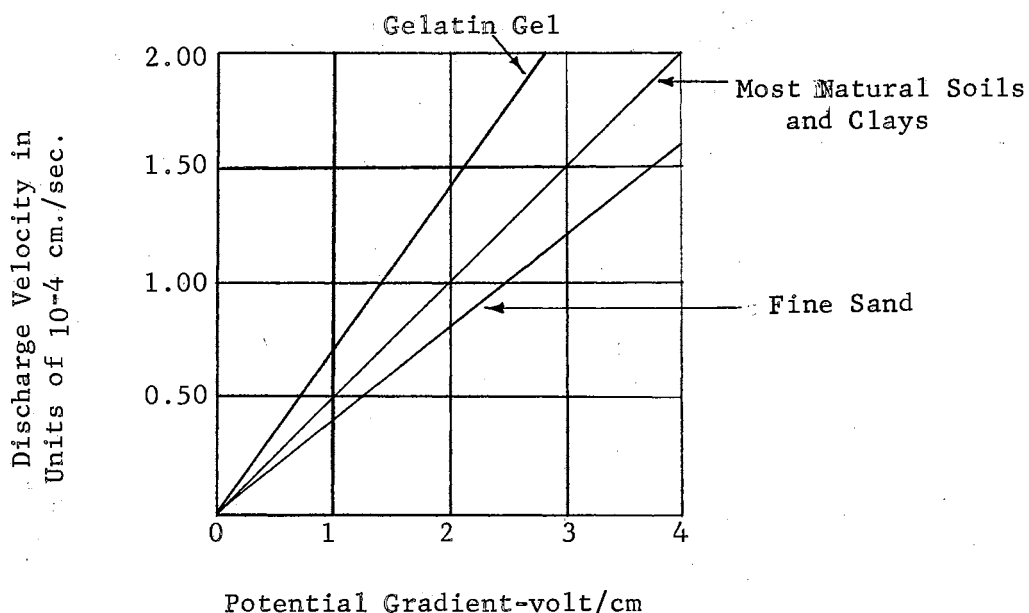


Figure 13. Relation between Electro-Osmotic Flow and Potential Gradient for Various Materials⁽¹⁵⁾.

The discharge of water at the cathode was found to be constant for all soils for a practically unlimited period of time when the surface was kept flooded and water was continually available at the anode. When the surface was not kept flooded, a constant flow was observed only for clean silts. Variations of flow with time under different conditions of test on London clay are shown in figure 14.

Determinations of water content at different distances from the electrodes at various intervals of time were made to study the movement of pore water in soil. In the case of a flooded surface, an increase in the water content in the upper part of the soil was noted, but no other change in pore water content took place, even near the electrodes. In the case of free water at the anode only, the distribution of pore water

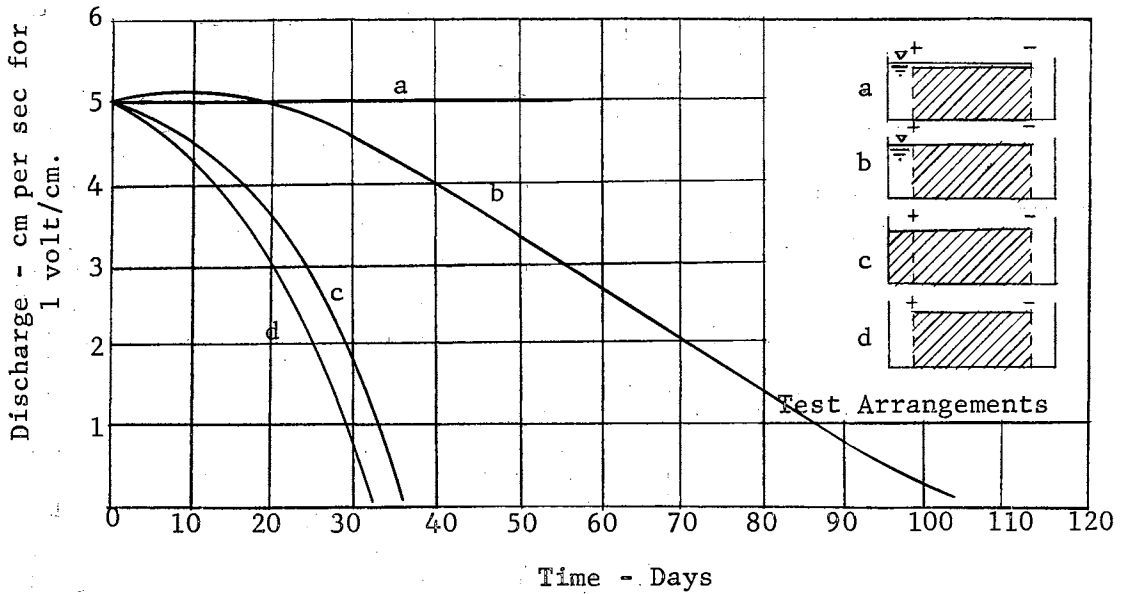


Figure 14. Discharge of Water from Model Tests on London Clay Under a Potential Gradient of 1 Volt per cm. (17).

became constant only after some period of time. The manner in which this occurred is shown in figure 15.

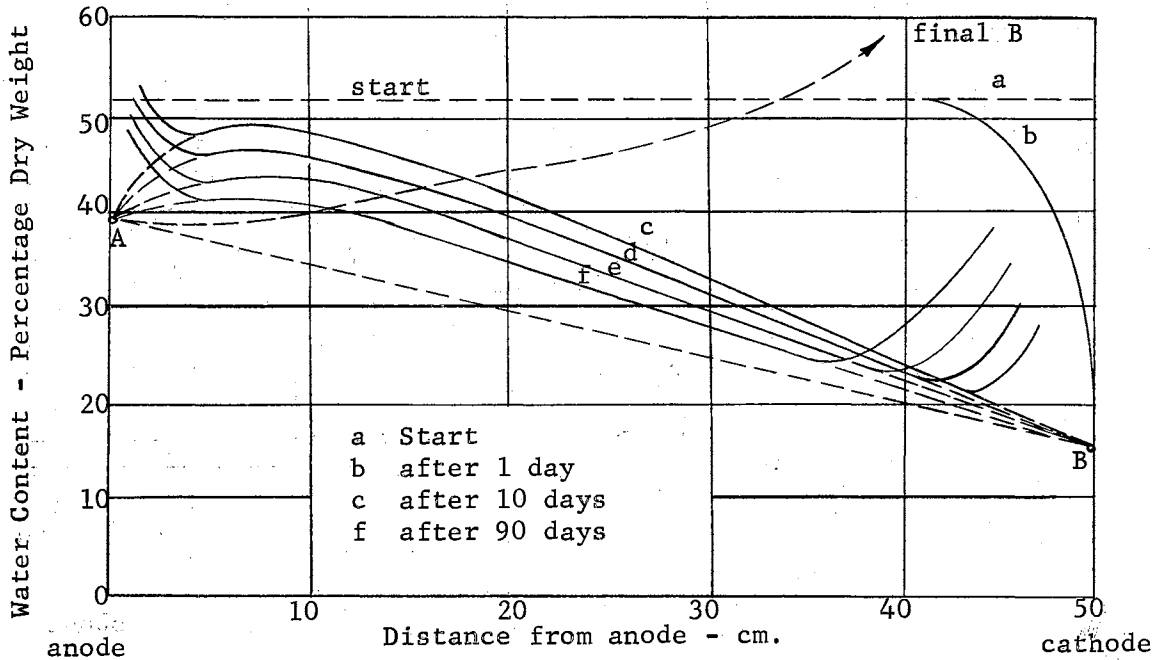


Figure 15. Distribution of Water Content in a Clayey Silt at Different Times after Start of Test (17).

The curves appear to converge on points A and B except for the irregularities in the vicinity of the electrodes. During the experiment the distribution curve changes gradually from curve a to curve f, and no further reduction in water content occurs. After a certain time, however, the discharge at the cathode decreases. While the water content is still decreasing at some distance from the cathode, it increases in the vicinity of the cathode and finally exceeds the original water content (final B). Casagrande⁽¹⁸⁾ attributes the accumulation of water partly to incrustations on the cathode gauze, but notes that a gradual concentration of water at the cathode cannot be prevented even with the cathode gauze working satisfactorily.

Rollins⁽¹⁹⁾ investigated the reduction in flow near cathodes. In his experiments radial flow was achieved in a cylindrical device. The anode comprised the vertical wall of the cylinder and the cathode consisted of a rod inserted vertically in the center of the cylinder. He also used an apparatus similar to the Casagrande device for parallel flow. The results achieved were not materially different for either device. The investigations show that electro-osmotic flow in soils of high calcium content causes considerable amounts of calcium hydroxide to be deposited at the cathode. The calcium hydroxide coats the metallic cathode, cements the soil particles and increases the density of the soil adjacent to the cathode. The first two effects considerably increase the electrical resistance of the soil. Consequently the flow of current is decreased, which is followed by a proportional decrease in the flow of water.

Further investigations into variations of electro-osmotic flow were performed by Rollins⁽²⁰⁾ on North Carolina kaolin. For most elec-

trodes used in electro-osmosis, the concentration of hydrogen ions is higher around the anode than in the remainder of the system, while the concentration of hydroxyl ions is increased at the cathode. On the basis of differences in ion mobility and conducting mechanism, it is concluded that flow in hydrogen saturated clay is less than in clay saturated with other ions. From experiments on kaolinite saturated with various ions, the flow rate was found to be in accord with the following sequence: $H < Fe < Ca < Na < Al$. Hence, the flow rate in a region of a soil-water system is considered to be dependent upon the ionic content of that region at any particular time. It is believed possible that the variation in the electro-osmotic flow rate is the explanation of such phenomena as development of moisture gradient, volume change, and changes in intergranular stresses and pore water stresses.

Consolidation

Geuze and others⁽²¹⁾ investigated the effects of electro-osmosis on consolidation of samples of heavy clay containing traces of peat. In the experiments a triaxial device was equipped with aluminum electrodes in the form of perforated circular plates, which were inserted between the ends of the sample and the porous stones. The samples, of 15 cm. length and 7 cm. diameter were subjected to a vertical static load and the lateral pressures developed were measured by the triaxial device.

Consolidation under load only, for about 20 hours, was followed by application of electricity for an additional 48 hour period. The results of the experiment are shown in figure 16. Almost immediately after closing the electrical circuit, the samples started to consolidate at accelerating speeds for a period of about 12 hours and then at slowly

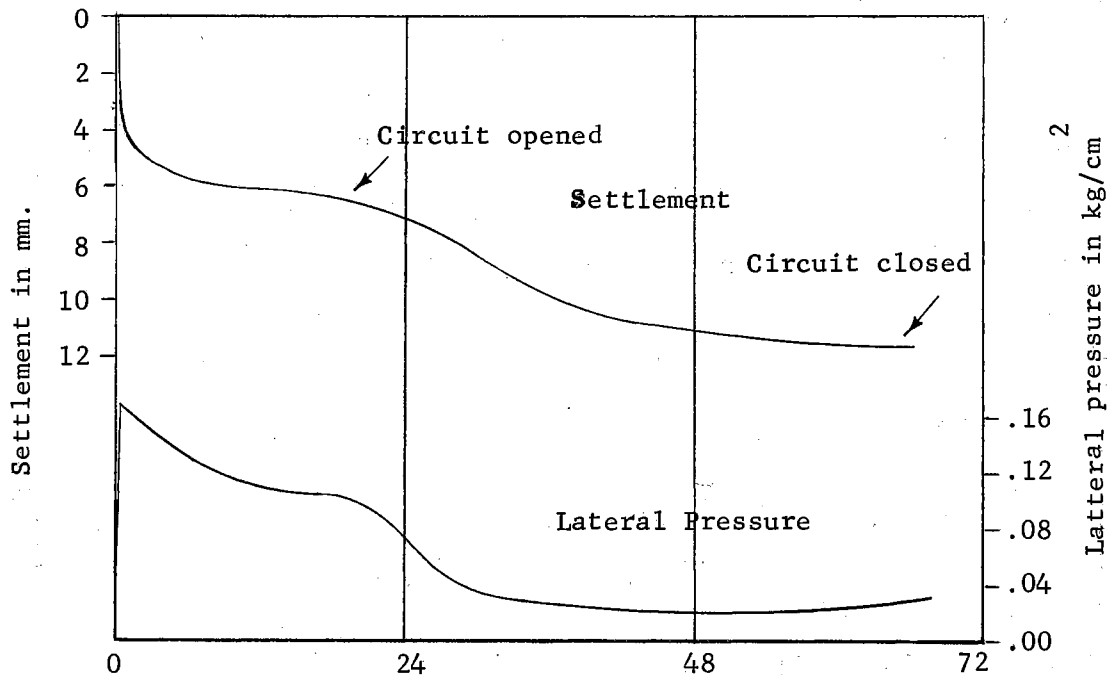


Figure 16. Settlement and Lateral Pressure under Electro-Osmosis (21)

decreasing speeds for the remainder of the period of treatment. The lateral pressures decreased in the same manner and a constant, minimum value was attained about 30 hours after starting the electric current.

Vey⁽¹⁶⁾ performed a similar experiment using a Casagrande consolidometer. In figure 17, curve number 1 is an ordinary consolidation curve ($e - \log P$) using increments of load only. Curve number 2 was obtained by using the same increments of load plus electrical treatment on a different sample of the same soil. These curves illustrate that no effect of electro-osmosis is evident until a certain critical load is reached. Additional increments of load beyond the critical load resulted in very little further consolidation. From the results of this experiment Vey concludes that consolidation in very fine grained soils by

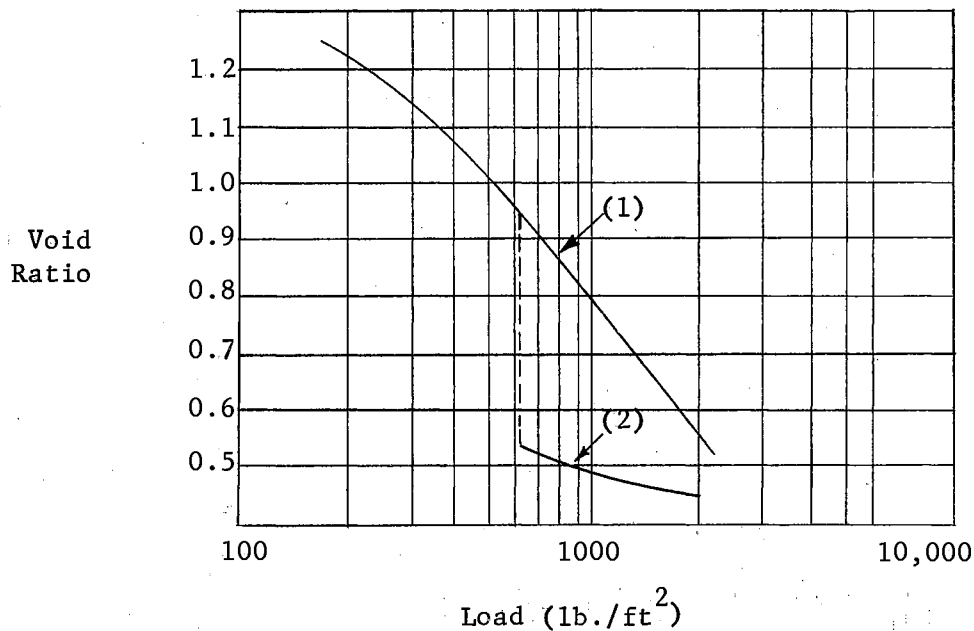


Figure 17. Effect of Electro-Osmosis on Load-Consolidation Curve (16)

electro-osmosis can be effectively accomplished only when applied in conjunction with a certain minimum consolidation load.

Casagrande⁽²²⁾ conducted consolidation tests on Boston Blue Clay to determine the effect of electro-osmosis on preconsolidation pressure. Several electrical consolidation tests were made with variations in the magnitude of impressed voltages and time of treatment. In the course of the experiments it was found that more pronounced change in preconsolidation pressure occurred under relatively low potential gradients over long periods of time. This was interpreted to mean that under low potential gradients the resulting structural rearrangement achieves better definition and proceeds more uniformly than in treatment under high potential gradients. Comparison of test results from treated and untreated samples indicates that the preconsolidation pressure

of the soil is increased by electro-osmosis, especially in the area near the anode. The slopes of the virgin compression curve and of the swelling curve apparently are unaffected by the process.

Stabilization

Karpoff⁽²³⁾ investigated the effects of electro-osmosis, and electro-osmosis in combination with chemical treatment, on the stability of fine grained soils. The apparatus used in this investigation resembled the Casagrande device except that the anodes were copper strips inserted vertically into the soil, and the cathodes were well-points. Two types of soil were investigated. The first type, a sandy silt, was investigated in the laboratory during development of testing techniques; the second, a medium fat clay, was investigated to check the technique and apparatus developed. Since the conclusions resulting from either experiment were not significantly different, only the first is here reviewed.

The first type of soil was obtained from the Granby Pump Canal of the Bureau of Reclamation Colorado-Big Thompson Project in Colorado. The sample used was classified as a cohesionless, fine, sandy silt of high water retention capacity. Tests made on the soil included grain size distribution, plasticity, standard compaction, triaxial shear, base exchange capacity, X-ray diffraction, microscopy, and others. The significant physical and chemical properties of the soil are listed in table II.

Separate samples of the soil were treated for 30 minutes each, by three different methods. In the first method, electro-osmosis was not used, but the soil was dewatered by application of a vacuum of 10 in. Hg. at the cathodic well points. In the second method electro-

TABLE II

SUMMARY OF THE LABORATORY TEST RESULTS

Effect of Electro-Osmotic and Electrochemical Treatment on
The Physical Properties of Granby Pump Canal Soils

Physical and Chemical Properties of Soil	Field Condition (average of three samples)	Method of Treatment of Soil		
		Well-points (vacuum 10 inches of Hg)	Electro-osmotic (emf 35v and vacuum 10 inches of Hg)	Electrochemical (emf 35v vacuum 10 inches of Hg and 4.3 ml of 2 percent Ca Cl ₂ solution)
Dry density, lb. per cu. ft.	94.6	100.7	103.4	102.8
Moisture content, percent	28.3	20.2	17.9	17.8
Penetration resistance, lb. per sq.in. (Proctor)	-	225.0	505.0	620.0
Internal friction, tangent ϕ	-	0.70	0.74	0.77
Cohesion, lb.per sq.in.	-	0	0	0.13
Slaking action of water, min.	Immediately	8.5	11.75	4320 +
Void ratio	0.74	0.63	0.59	0.60
Permeability, ft.per yr.-20°C	14.73	-	9.91	-
Exchange capacity, me.per 100 gr.	12.38	12.38	at anode 11.25 at cathode 11.75	at anode 8.75 at cathode 9.26
Energy requirement per sample, watt-hour	-	-	0.63	1.18
Dewatering rate of sample, ml.permin.	-	-	0.46	0.62

osmosis under a potential of 35 volts was used in combination with the vacuum. In the third method a chemical solution (2% CaCl_2) was applied at the anode simultaneously with the application of the electric potential and the vacuum. After treatment in each experiment, the chemical and physical properties of the soil were again tested to provide a comparison with those obtained before treatment. The results obtained from the data of laboratory tests are summarized in table II. An examination of the table reveals the following changes: (1) decrease in moisture content, (2) increase in density, (3) increase in cohesion, (4) increase in penetration resistance, (5) increase in internal friction, (6) change in base exchange capacity, (7) change in permeability, and (8) increased resistance to slaking in water.

In regard to the decrease in base exchange capacity as a result of treatment, it is considered that the electro-osmotic and electro-chemical methods of stabilization of soil not only cause a reduction in the water content of the soil but at the same time bring about changes in the physicochemical properties of the material and possible changes in the structure of the clay particles. Hence, the changes in the physicochemical properties are also partly responsible for the improved engineering properties of the material.

It is believed that due to the uniform grading of the soil samples, some colloidal particles were detached by the electro-osmotic forces and migrated through the water filled void spaces of the soil toward the anode, thereby forming a more impervious media in that vicinity. This is assumed to be the explanation for the decrease in the value of the coefficient of permeability of the soil after electro-osmotic and vacuum application.

Spangler and King⁽²⁴⁾ conducted a laboratory study to investigate further the Casagrande method of electro-chemical stabilization of soils in the vicinity of aluminum friction piles. A series of model piles consisting of $\frac{1}{2}$ in. diameter aluminum alloy rods were driven into various soils contained in water proof boxes. The soils were mixtures of various materials, and the two-micron clay content ranged from 2.8 to 48 percent. Half the soils were kaolinitic and half were montmorillonitic. The soils were kept saturated during the experiments by maintaining a layer of water about $\frac{1}{2}$ in. deep over the soil.

After the piles were driven the "bearing capacity" of each of the piles was determined, according to an arbitrarily established standard, as the load which caused a pile to settle a distance of .01 mm. in 30 sec. Then a direct current was applied to the piles in pairs, and the amount of current and voltage were measured. During the treatment period, measurements of the bearing capacities were frequently made. It was found that in all cases the bearing capacity increased to a maximum value as treatment progressed, and that further treatment caused a marked decline in the bearing capacity. It was found that the maximum bearing capacity and the energy requirements for optimum treatment increased as the two-micron clay content of the soils increased. The energy requirement for optimum treatment of the negative piles was found in every case to be greater than for the positive piles. However, there was no definite relationship between the maximum increase in bearing capacity and the polarity of the piles.

After electrical treatment was discontinued, the piles were pulled from the soil. It was found that the soil in the immediate vicinity of the piles was impregnated with a substance which seemed to cement the grains of soil together and which probably accounted for the increase

in bearing capacity of the piles. A white, powdery substance had formed at the surface of the piles and appeared to have reduced the skin friction between the piles and the adjacent soil, in the later stages of treatment. A cylindrical mass of soil adhered to a few of the cathodic piles. All of the piles were extensively corroded as a result of the treatment.

It is thought that in the early period of electrical treatment, the bearing capacity is increased due to the deposition of insoluble salts in the soil. Other factors such as water content, base exchange, etc., also influence the increase in strength. As treatment progresses deposition of the white powdery substance, which has been found to be chemically the same as the mineral bauxite, causes a gradual reduction in the skin friction of the piles. Finally, the reduction in skin friction becomes so great that it begins to offset the increase in soil strength, and when this takes place the optimum effect of electrochemical treatment has been reached. Continuation of the treatment then causes a reduction in pile bearing capacity.

CHAPTER V
PRACTICAL APPLICATIONS

The First Practical Application

Electro-osmotic control of unstable soil conditions was applied for the first time in 1939 by Casagrande⁽¹⁵⁾ in the excavation of a railroad cut at Salzgitter, Germany. A cut 21 feet in depth was required on the project. When excavation reached a depth of about six feet the side slopes readily flowed due to instability. A test well installation revealed that because of the fine texture of the soil, well points would not be effective in stabilizing the slopes. It was then apparent that excavation could be continued only if the side slopes were made very flat, and this would have greatly increased the amount of material to be removed.

A trial section for the application of electro-osmosis was installed along 300 feet of the cut. Cathodes of 4 in. slotted steel pipes were driven 22.5 ft. into the ground at intervals of 30 ft. along the top of both sides of the excavation. Lengths of one-half in. gas pipe were used as anodes and were driven halfway between the cathodes. Within a few hours after the application of 180 volts the condition of the slopes improved to an extent that excavation could be resumed and in one or two days power shovels were able to operate from inside the cut. At this stage the potential was reduced to 90 volts and remained at that level until completion of the work. The power consumed amounted to approximately

1.7 kilowatt per cathode in the beginning and gradually reduced to 1.2 kilowatt after a few weeks. The total energy consumed for cu.yd. of excavation was approximately one kilowatt-hour. At the completion of the construction the bottom and sides of the cut were covered with a sand filter and a drainage pipe was installed along both sides of the cut to prevent damage from seepage after electro-osmosis was stopped.

U-Boat Pens in Norway

An extensive application of stabilization by electro-osmosis was made by Casagrande^(6,15) in connection with the construction of the U-Boat pens at Trondhjem, Norway. The pens were constructed on a rather flat area extending into a fiord, the surface of which was only a few feet below the level of the ground. The subsoil consisted of uniform, very silty clay, which extended to several hundred feet in depth. In the undisturbed state the material was soft and on remolding became almost liquified.

An excavation to a depth of about fifty feet was required for the project. Because of the open water immediately adjacent to the area, the site was surrounded by two rows of steel sheet piling with an imbedded depth of 65 feet. In addition, two berms were constructed to add to the stability of the excavation as illustrated in figure 18.

When the excavation reached a depth of about 15 feet, the unbalanced hydrostatic head caused a considerable flow of water upward into the excavation. In one area a lengthy portion of sheetpile moved horizontally toward the excavation without tilting and in other areas the sheet piling partially collapsed by tilting. When a depth of about 23 feet was reached, the ground heaved and in a few seconds filled the

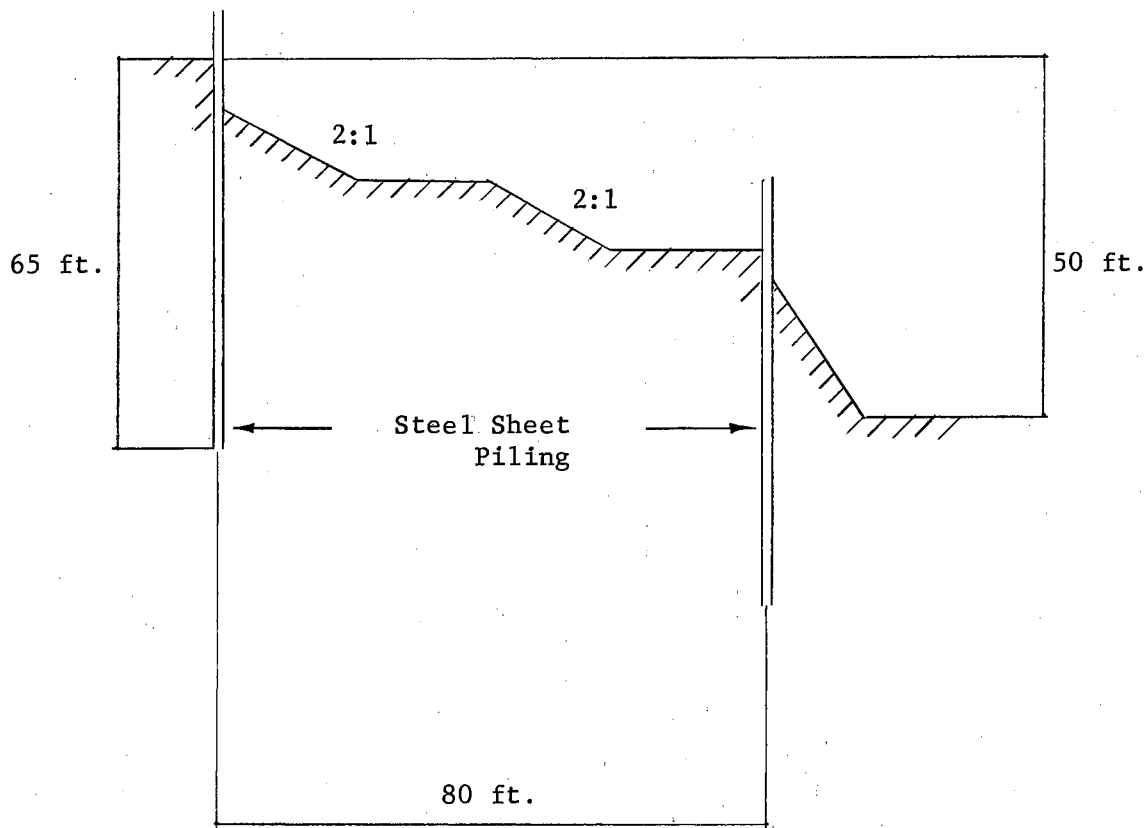


Figure 18. Section Through Slope of Excavation for U-Boat Pen in Norway (15).

holes being dug by clamshell buckets. Further progress was therefore impossible since the soil flowed into the excavation as fast as it was being removed, and the work came to a halt.

Two rows of electrodes were driven to a depth of 60 feet. The cathodes consisted of slotted 8 inch pipes covered with a fine copper mesh, and were spaced 30 feet apart. Common gas pipe was used for the anodes which were located half way between the cathodes. The initial voltage applied was 90 volts, but because of a high concentration of salts in the soil, it was reduced to 40 volts in order not to exceed the allowable output of the generator. Two days after the potential was

applied to the electrodes, the excavation was continued without further difficulty. The power consumed was .4 kilowatt-hour per cu.yd. excavated.

The Power Plant in Joppa, Illinois

Electro-osmosis was used in slope stabilization in the construction of a generating unit at a power plant in Joppa, Illinois⁽²⁵⁾. In 1951 four generator units were built with foundations on a sand and gravel stratum at a depth of about 65 ft. below the general site grade. On completion of unit number 4, the foundation excavation was backfilled to grade with a soft clay, which was dumped in the loose state. No effort was made to place the fill in lifts and compact it. The extent of the fill is shown in figure 19. Some time after the fill was completed, bearing piles were driven through it to the hard layer below, to carry crane rails and stator paths.

In 1953 excavation began for a fifth generator unit adjacent to unit number 4. Because the existing crane rails and stator paths limited the excavation, it was not possible to provide a moderately inclined slope in the area. Instead, it was planned to open-cut the area from elevation 350 to elevation 325 only, and then drive steel sheet piling to hold the rest of the excavation down to final grade at elevation 306. Upon excavating to elevation 325, the soil moved forward toward the cut so much, that some bearing piles for the crane rails were sheared off, permanent steel sheeting around the craneway ends was displaced, and a ground level concrete slab cracked and settled as much as 1½ ft. due to loss of soil. A 140 ft. line of steel sheet piling was driven from elevation 325 to elevation 290. With 19 ft. of excavation remaining, and with the bank already moving in toward the hole, it became

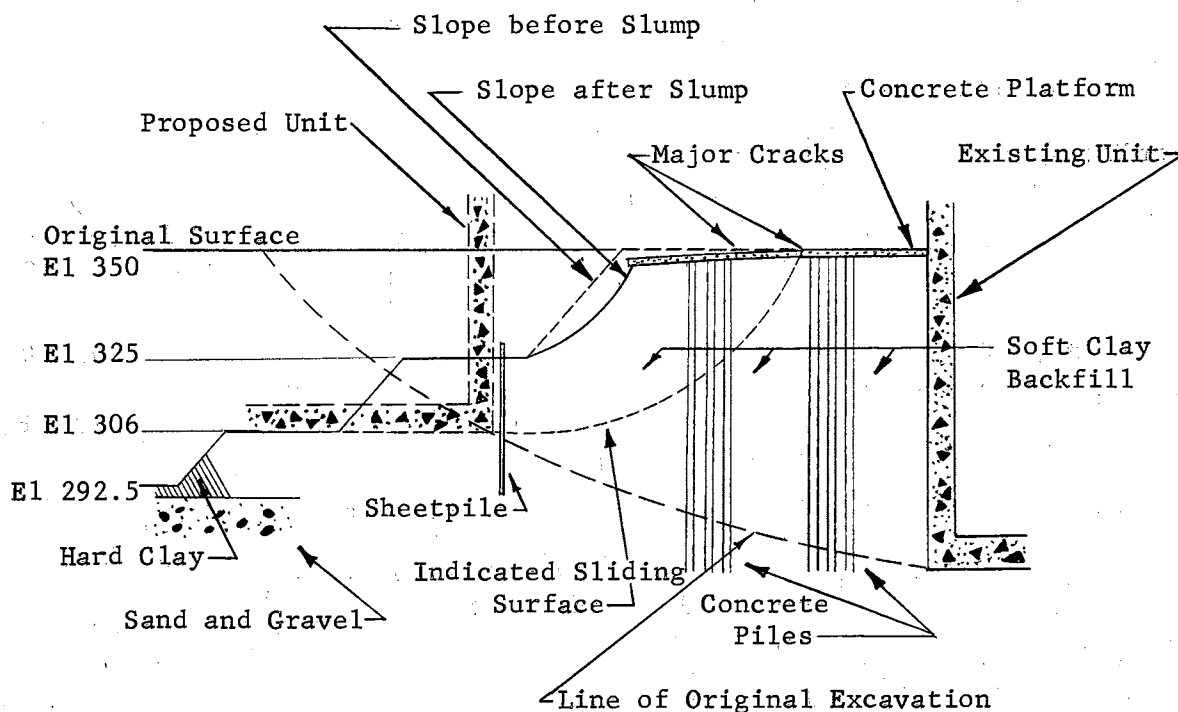


Figure 19. Typical Cross Section Before Electrical Treatment

apparent that stabilization or containment of the slope would be required before digging could continue. Up to this time, the movement of the slope had been forward, but a greater danger existed in the possibility of the entire mass of backfill sliding into the excavation when the counterbalancing weight of the berm, which extended 40 ft. beyond the toe, would be removed. Removal of the berm might have permitted the entire soft clay bank to rotate on sliding, with a resultant shearing of the remaining

intact piles in the backfill area.

The slope, over a length of 150 ft. and a width of 75 ft., was treated with electro-osmosis using three 70-KW D.C. generators and a potential of 90 volts. Alternate anodes and cathodes were driven to elevation 300 on 5 ft. centers in a checkerboard pattern. The length of the embedded electrodes varied from about 25 to 50 ft., depending on location on the slope. The anodes consisted of 1.5 in. diameter steel pipes with a 1 in. reinforcing rod driven down inside them. The cathodes were 1.5 in. vacuum wellpoints with a vacuum of 27 in. of Hg. applied. The increase of strength of the treated soil during electrical treatment was checked by means of in-situ vane tests and with unconfined compression tests. The shearing resistance of the soil increased from 21 ft.lb. before treatment to more than 100 ft.lb. after treatment, as measured by a Swedish vane. Unconfined compression tests showed the average original strength of 0.19 tons per sq.ft. increased to 1.87 tons per sq.ft. During treatment the water content was reduced from an average of 25.8% to an average of 19.2%.

Full Scale Pile Tests

In 1937 Casagrande⁽²⁹⁾ undertook full scale tests of electro-osmotic treatment on wooden friction piles sheathed with aluminum. The location selected was near the Reichsautobahn in the area near Chiernsee. The site was covered with 8 to 12 in. of water. Borings to a depth of about 200 ft. were taken to determine the nature of the soil. It was found to be a homogeneous clayey silt at all elevations except the upper 6.5 ft. which contained some humus material. The moisture content was slightly below the liquid limit. A mechanical analysis indicated that

the 2-micron clay particle content was about 3 percent.

Six wooden piles about 1 ft. in diameter were driven to a depth of approximately 20 ft. The embedded length of each pile was sheathed with aluminum of 1 mm. thickness. Three pairs of piles were spaced 4, 5 and 6 feet apart respectively. They were driven by a single acting steam hammer, the moving portion of which weighed 3500 lbs. The length of the fall of the hammer was 10 in. All of the piles penetrated about 6.5 ft. from the dead weight of the hammer alone. During driving each pile penetrated about 12 in. per blow. After driving, loading tests indicated that the bearing capacity of the piles was between 7 and 9 tons per pile.

The first pair of piles was placed under a potential of 220 volts which resulted in a current flow of from 40 to 60 amperes. About 1100 kilowatt hours of energy were expended in the treatment. The second pair of piles was treated in the same manner until about 260 kilowatt hours of energy were utilized. Then the second and third pairs were connected in parallel under a potential of 110 volts, until each pair had consumed about 25 amperes. The second pair received 60 kilowatt hours under this arrangement for a total of 320 kilowatt hours. The third pair of piles received only 60 kilowatt hours of treatment. A considerable amount of gas evolved at both electrodes during treatment. Loading tests were made on the piles as treatment progressed. In these tests it was noted that the bearing capacity of the piles increased to a maximum value and then decreased. The average maximum strength of the piles was 40 tons per pile which was reached after about 30 kilowatt hours of energy had been consumed. After the tests were completed the piles were pulled and it was noted that the soil near the piles was hard-

ened to distances up to 12 in. from the pile surface.

The Big Pic River Bridge

Casagrande⁽²⁶⁾ utilized electro-osmotic treatment on piles at the Big Pic River Bridge, Ontario, Canada. The soil profile at the site consists of a layer of clayey fine sand 10 to 20 ft. thick above a 30 to 50 ft. thick layer of varved clay of soft to firm consistency. Beneath the varved clay there exists a several hundred feet thick stratum of loose to medium dense inorganic silt. The natural water content of the clay layers in the varved clay is from 56 to 62% which is approximately at the liquid limit. The clay becomes very soft and sticky upon remolding.

Because of the great depth of soil above bedrock, the design required the bridge piers and abutments to be founded on friction piles with a maximum load of 15 tons per pile. To disturb the soil the least amount possible, it was decided to use 12 in. H-piles. Load tests indicated that the bearing capacity of the piles decreased upon penetrating the silt stratum. Piles, 56 ft. in length, which did not extend into the silt stratum failed when loaded between 20 and 30 tons. For a 168 ft. long pile, however, the bearing capacity dropped as low as 10 tons. It was concluded that the decrease in bearing capacity of the piles extending into the silt stratum was probably due to the existence of artesian pressure in this stratum. Several months after driving, renewed load tests on these piles showed that the bearing capacity had not increased in the interim.

After laboratory investigations and a field test indicated an appreciable increase in bearing capacity of the piles after several hours

of treatment by electro-osmosis, it was decided to construct the bridge footings on 56 ft. long H-piles and to utilize electro-osmosis to increase the frictional resistance of the piles. The H-piles were used as anodes and cathodic wellpoints were arranged at an average distance of 25 ft. surrounding the bridge footings. An electrical potential of approximately 100 volts was applied which resulted in an average potential gradient of 0.13 volts/cm. The current fluctuated between a wide range of 5 to 50 amperes per pile, with the majority of piles carrying approximately 15 amperes.

Electrical treatment was applied for a period of four weeks, and a number of piles were load-tested at weekly intervals during the process. Because of limitations of the load-testing arrangement, the majority of the piles were load tested only from 60 to 65 tons, with total settlements under these loads averaging 0.2 in. After strengthening the load-testing facilities, several piles were loaded to 100 tons with total settlements of 0.5 to 0.7 in., and a permanent deflection, after rebound, of 0.3 in. to 0.4 in. As a result of these tests it was concluded that an ample safety factor exists for the design load of 15 tons per pile.

Lowering the Water Level in Mexico City

The high compressibility and great thickness of the deposits of lacustrine clay, of volcanic origin, above which the greater part of Mexico City is constructed, impose in many cases the necessity of resorting to floating foundations⁽²⁷⁾. This requires the carrying out of an excavation which frequently reaches a depth of 6 m. and even greater. The removal of the soil during the excavation reduces the load on the underlying clay strata which results in an expansion, the magnitude of

which is dependent upon the area and depth of the excavation. It has been observed that the soil rises on the order of 40 cm. in an excavation of 6.5 m. in depth over an area of 12 x 60 m.

The nature of the phenomena of the expansion of clays in the Valley of Mexico has not been fully studied. Investigations in the laboratory and in the field indicate that the phenomenon takes place in two stages. The first stage consists of a relatively rapid expansion, which is apparently an elastic phenomenon and which takes place at a rate proportional to the advance of the excavation. The second phase, which takes place more slowly, is accompanied by a change in the water content of the clay, and is a process which is prolonged for several years. The recompression of the clay which follows the application of structural load, produces settlements whose development in the course of time is almost unpredictable. This situation requires precautions during excavation to minimize the expansions. One of the procedures recently employed consists of lowering the water level in the vicinity of the excavation. This causes an overload or increase in overburden which if possible is made of such magnitude that it equals the reduction in pressure due to excavation.

The preceding principle is simple enough, but its application presents a problem of a practical nature. The low hydraulic permeability of the clays, which is on the order of 10^{-7} cm./sec., is such that removal of water by wellpoints is a slow process with consequent delays in the execution of the work. In order to accelerate the lowering of the water level, electro-osmosis was employed. The electro-osmotic permeability of some clays in the Valley of Mexico is about 0.2×10^{-4} cm./sec./volt/cm.

To determine the difference in the rate of lowering the water level by pumping alone, and pumping in conjunction with electro-osmosis in excavating for a building foundation, a field test was conducted. Four cathodic wellpoints were installed to a depth of 12 m. on the corners of a square of sides 4 m. in length. At the center of the square an anode was installed which consisted of four tubes of copper $\frac{1}{2}$ " in diameter and 8 m. in length located at the four corners of a 25 cm. square. Three piezometers were installed at 8 m. depth and were located as follows: one in the center of the anode, the second between two cathodes, and the third at 7 m. outside of the square bounded by the cathodes. In addition three piezometric cells were installed to measure the pressure in the water.

The test results indicated that the rate of lowering of the water level by pumping alone was 12 cm. per day, while by pumping in combination with electro-osmosis the rate was 72 cm. per day. The maximum discharge by pumping alone was 9,090 liters per day, and with pumping and electro-osmosis combined the maximum was 31,500 liters per day. The intensity of the current was initially 28.5 amperes per cathode and diminished to 11.2 amperes after 4 days.

As a consequence to these test results, the electro-osmotic process was applied to lowering the water level ahead of the excavation for the foundation of a building. An electrical gradient of 0.25 volts/cm in combination with pumping lowered the water level at a rate of 38 cm. per day to a depth of 7 m. below its original level, resulting in a surcharge of 7 tons/m². The expansion of the bottom of the zone excavated to a depth of 6.5 m. was 12.5 cm. On the basis of local experience, it was considered that the expansion would have been about 26 cm. if the

water level had not been lowered ahead of the excavation.

Electrical Equipment and Field Layout

Casagrande⁽¹⁷⁾ lists the following equation as a means of estimating the current flow between two cylindrical electrodes of equal length, but of different cross sectional area:

$$I = \pi s L E \left(\frac{1}{\ln \frac{d}{r_1}} + \frac{1}{\ln \frac{d}{r_2}} \right)$$

where I = current flow in amperes

s = the specific conductivity of the ground in amperes per cm^2 per volt per cm.

L = the length of the electrodes in cm.

r_1 and r_2 = the radii of the electrodes in cm.

d = the distance between the anode and cathode in cm.

E = applied potential in volts

The flow of current may also be estimated from the results of model tests. In this case the power consumed is observed on a model using a specimen of the soil in the field. The power required for the project is then taken as directly proportional to the scale which is used. If a supply of direct current is not available in the field, any type of direct current generator unit is suitable for use in electro-osmosis if it has the capability of providing continuous service for extended periods. Up to 220 volts may be required, depending on soil conditions, but a potential of 100 volts will be sufficient in most instances. A potential gradient of 0.5 volts per cm. should not be exceeded in order to prevent excessive loss of energy due to heating of the ground. The unit should have a high

current capacity, generally not less than 150 amperes. If exceptionally high current is encountered, as in the case of soils having a high electrolytic content, a means of reducing the voltage should be available.

A source of power for emergency use in case of breakdown should be available at all times since the flow of water will stop and then be reversed if current flow is discontinued. Casagrande⁽¹⁷⁾ considers that if current flow ceases for short intervals not exceeding a few minutes, stability will not be affected, not even in relatively permeable silty soils, and that if pumping from cathodic wells is continued, blow-ups or cave-ins are likely to occur only after the current has been stopped for a few hours. Karpoff⁽²³⁾ determined in the case of a laboratory test on a fine sandy silt, that the phreatic line which had been lowered by 20 minutes of electro-osmotic treatment under 35 volts, did not recover under 7 in. of hydraulic head until the elapse of 178 hours, and on this basis considered that a saving in power can be achieved by intermittent operation in actual practice.

No single rule determines the general layout of electrodes at the site, since this is dependent on several variables such as soil and moisture conditions, power supply available, etc. Anodes may be composed of old iron pipes of 1 or 2 in diameter, or the sheetpiles of an excavation may be employed. The individual pipes forming an anode should not be placed closer together than 2 ft. or the group will act as a single electrode of diameter only slightly larger than that of the individual pipes. Wellpoints or vacuum wellpoints have been used as cathodes in most recent applications. If the Casagrande hardening process is to be employed, both electrodes must be of aluminum or aluminum alloy.

The length of the electrodes and the spacing between them will

differ in every practical case. The common arrangements suggested by Casagrande in applying electro-osmosis to stabilizing slopes and bottoms of shallow, medium and deep excavations in silty ground are shown in figure 20. In general, the anodes and cathodes should extend to equal depths in the soil, however, there may be occasions where such a procedure is not suitable or possible. While cathodes should penetrate to 1.5 times the depth of the excavation, especially in soft, cohesionless ground, shorter wells may be permissible in other cases.

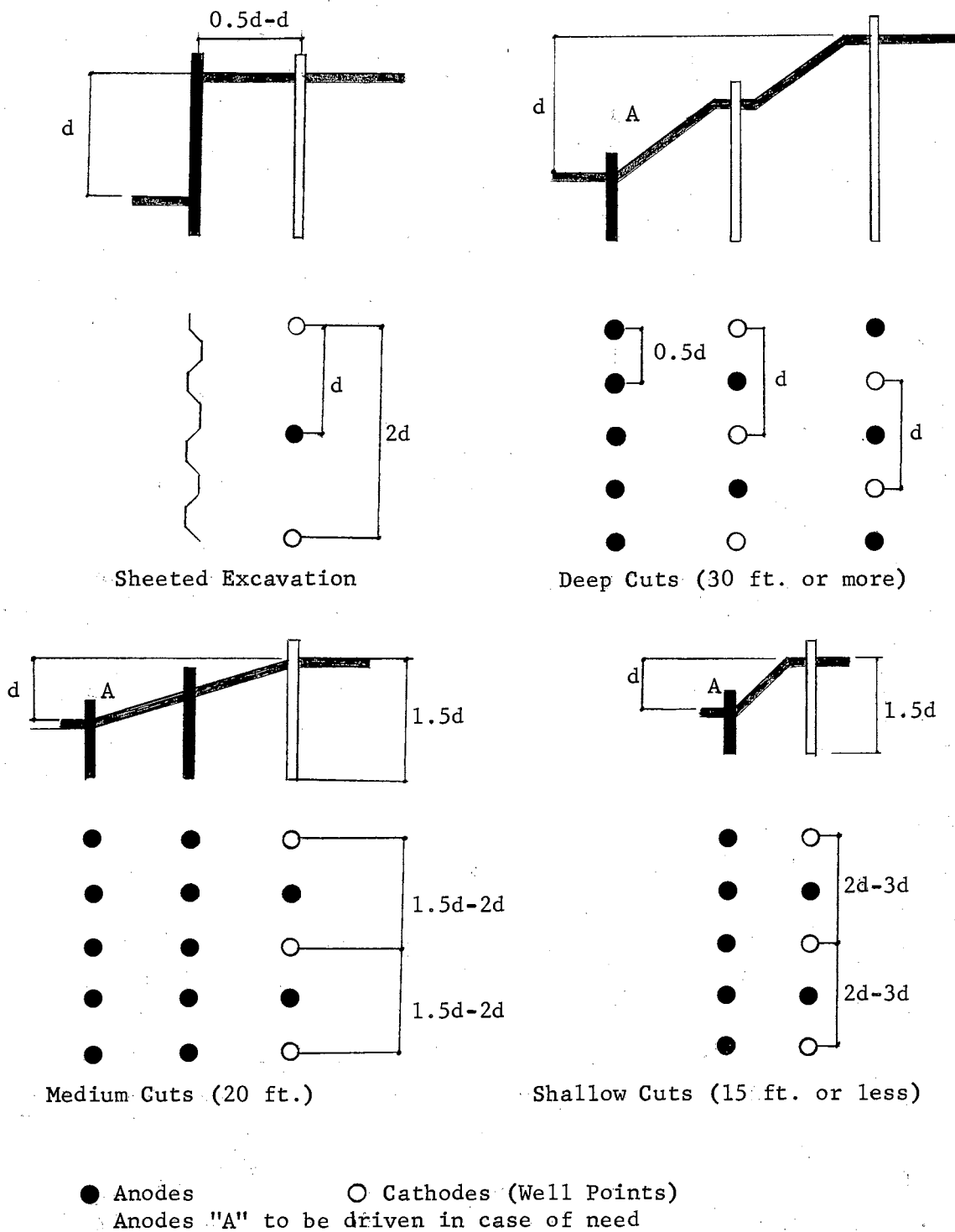


Figure 20. Arrangement of Electrodes in Cuts (17)

CHAPTER VI

SUMMARY AND CONCLUSION

Soil particles in water comprise a colloidal system and acquire a charge as a result of selective adsorption of ions and dipolar water molecules. The charge on the colloid together with the attracted ions neutralizing it constitute a double layer. The formation of a double layer is affected not only by electrostatic forces but also by those of thermal agitation and by van der Waal's forces of universal attraction. Stern's concept of the double layer is essentially a combination of the Helmholtz and Gouy-Chapman double layers, and shows the variation of the zeta potential with distance from the colloid. Addition of electrolytes to a colloidal system may reduce the zeta potential to zero or even reverse it, thereby collapsing and reforming a double layer. Although base exchange takes place in the lattice structure, the predominant exchange occurs in the double layer.

Electro-osmosis is the phenomenon of liquid moving through a porous medium under the influence of an electrical field. The flow of water is caused by motion of the ions in the diffuse portion of the double layer, and may be computed from the value of the zeta potential and other factors. Restricted electro-osmotic flow results in a pressure head, the magnitude of which may be calculated. The electro-osmotic pressure head may be considered as an additional load in the consolidation process, but consolidation is complicated by the capillary structure of fine

grained soils. *(The following is a summary of the general results.)*

Reduction of water content and void ratio in the consolidation process increases the stability of soils. Stability is only temporarily achieved by the use of electro-osmosis alone, but stability of a permanent nature can be accomplished by cementation and ionic exchange from electro-osmosis combined with the introduction of chemicals, or ions from aluminum electrodes. Laboratory investigations indicate the rate of electro-osmotic flow to be proportional to the potential gradient. The reduction of water at the anodes remains in effect during electro-osmotic treatment, but cementation and base exchange at the cathode results in restricted flow and increased water content during the later stages of treatment. The flow of water through the soil is shown to be dependent on the ionic content of a particular region at any time, which affords a basis for explanation of certain phenomena such as moisture gradient, and variation in intergranular stresses.

It is demonstrated that consolidation of colloidal soils by electro-osmosis can be accomplished effectively when applied in conjunction with a minimum consolidation load. Tests using electro-osmotic and electrochemical treatment show that the processes improve many of the engineering properties of the soil, such as resistance to penetration, and resistance to slaking. Soil around model piles, when treated by electrochemical stabilization in laboratory tests, was found to harden and thereby increase the load carrying capacity of the piles.

The first practical application of electro-osmosis in a railroad cut successfully treated the highly unstable soil and enabled excavation to continue. A similar result on a large scale was achieved at the U-Boat pens in Norway. Recently the process was applied to the excavation of a power plant unit in Illinois. Electro-osmosis was found

successful in lowering the water level at an excavation in Mexico City clay, and in increasing the carrying capacity of friction piles at the Big Pic River Bridge.

The power requirements for application of electro-osmosis in the field may be estimated from a given formula or from scale model tests. Requirements for practical application include a dependable source of direct current, anodes of some relatively inexpensive metal, and cathodes preferably in the form of well points or vacuum well points. Intermittent operation may be practiced if stability is not impaired, and will result in a reduction of power consumption.

The physicochemical properties of the soil-water system exert a controlling influence on the electro-osmotic process. The formation of a double layer of greater average thickness occurs in soils having appreciable amounts of active minerals than in soils of relatively inactive constituents. The concentration of ions at a point in the double layer is indicated by the magnitude of the zeta potential. The movement of pore water in soils by electro-osmosis is dependent upon the existence of a double layer, and it has been shown that, other factors being equal, the flow of water in electro-osmosis is directly proportional to the zeta potential.

One of the limitations inherent in the evaluation of electro-osmotic flow rate from calculations including the zeta potential as a factor is that local variations in the constituents of the soil may vary the magnitude of the zeta potential. Since representative sampling for determination of the zeta potential is difficult to obtain, the flow as determined by calculation may differ from that which actually occurs in the soil-water system. In addition to local variations in the zeta po-

tential, it must be considered that the concentration and type of ions present in the soil-water system is continually changing during electro-osmosis as a result of movement of ions toward the electrodes and by the addition of hydrogen and hydroxyl ions to the system at the anodes and cathodes respectively. Therefore the zeta potential at a point is unlikely to be the same at any two times during the application of electro-osmosis. Hence, for practical applications, determination of electro-osmotic flow rate on the basis of scale model tests appears to be a better indication of actual conditions than the value calculated from theoretical considerations.

The increase in stability of the soil as a result of electro-osmosis is dependent upon the factors which influence the rate of electro-osmotic flow. The reduction of water content, the increase in pore water tension, and the increase in shear strength, which are all associated with soil stability, are therefore dependent upon the physicochemical properties of the soil. For example, it may be expected that the development of pore water tensions in clay requires a longer period of treatment than the development of equal tensions in silt due to the difference in the size of the pores of the two materials. Therefore it is concluded that the extent of improvement in the stability of a soil as a result of electro-osmotic treatment is a consequence which cannot accurately be predicted. Scale model tests again appear to be of value in making reasonable estimates.

Since the results of scale model tests on electro-osmotic flow and resultant stability are related to actual field conditions only to the extent that the soil used in the tests compares with that in the field, the need for representative sampling in electro-osmotic experi-

mentation is at least as important as that in any other phase of soil mechanics. The best results in predicting the effects of electro-osmosis are considered to be achieved by conducting field tests.

Treatment of soil by electro-osmosis alone, produces highly beneficial results of a temporary nature in improving the stability of cuts and embankments, and in increasing the rate of lowering the water level. Equally significant stabilization of a permanent nature is accomplished by electrochemical stabilization. Since permanent improvement by electrochemical stabilization proceeds slowly from the electrodes, this method of treatment appears applicable where small masses are to be stabilized as in the case of strengthening the soil around friction piles to increase the load-carrying capacity. In both electro-osmosis alone and in electrochemical chemical stabilization, corrosion of the electrodes may be a significant consideration in determining the allowable extent of application. If metal sheetpiling in electro-osmosis or metal piles in electrochemical stabilization are used as electrodes; the effect of corrosion on the strength of the materials may not be overlooked without accepting the consequences. The literature presently available offers no effective method of controlling the progress of corrosion. Therefore, when corrosion of structural members is involved, electro-osmosis should be used with caution.

In any consideration of the application of electro-osmosis, the economics of the process should govern the final decision as to whether or not it will be employed. In addition to the power requirements, the cost of installation, and replacement of corroded electrodes appear to be significant items. The proponents of electro-osmosis claim it economical to employ, but since only limited data on the cost

of the process appear in the literature, a general statement on the economic feasibility does not seem warranted. The decision to use the process in lieu of another, depends on the circumstances at hand and ultimately upon the judgment of the engineer.

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