PHOTOGRAPH THIS SHEET

ADA081137

DTIC ACCESSION NUMBER

II

LEVEL

INVENTORY

AEWES Misc. Paper No. 3-122, Rpt. No. 7, Dtd. Oct. 1961

DOCUMENT IDENTIFICATION

DISTRIBUTION STATEMENT A

Approved for public release; Distribution Unlimited

DISTRIBUTION STATEMENT

ACCESSION FOR		
NTIS	GRA&I	☒
DTIC	TAB	☐
UNANNOUNCED		☐
JUSTIFICATION		
Per Ltr. on file		
BY		
DISTRIBUTION /		
AVAILABILITY CODES		
DIST	AVAIL AND/OR SPECIAL	
A		

DISTRIBUTION STAMP

DTIC
ELECTE
FEB 28 1980
S D
D

DATE ACCESSIONED

80 2 27 072

DATE RECEIVED IN DTIC

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-DDA-2

DTIC FORM OCT 79 70A

DOCUMENT PROCESSING SHEET

SUMMARY REVIEWS OF SOIL STABILIZATION PROCESSES

ELECTRICAL STABILIZATION OF FINE-GRAINED SOILS

MISCELLANEOUS PAPER NO. 3-122

Report 7

October 1961

U. S. Army Engineer Waterways Experiment Station

CORPS OF ENGINEERS

Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

PREFACE

This report was prepared for the Office, Chief of Engineers, under the authority of Project 8S70-05-001, "Trafficability and Mobility Research," Task 05, "Mobility Engineering Support," to satisfy a portion of the objectives of the soil stabilization research program.

The report summarizes available literature and information pertaining to the use of electrical methods for stabilizing and/or altering the physical characteristics of fine-grained soils. The review was made by Messrs. D. R. Freitag, formerly Chief, Soils Stabilization Section, G. R. Kozan, and W. B. Fenwick, under the general direction of Messrs. W. J. Turnbull and W. G. Shockley, Soils Division. This report was prepared by Messrs. Kozan and Fenwick.

Col. Edmund H. Lang, CE, was Director of the Waterways Experiment Station during the preparation of this report. Mr. J. B. Tiffany was Technical Director.

CONTENTS

SUMMARY

A review of literature on soil stabilization by electrical methods is presented, with particular emphasis on the techniques that might be applied by the military to improve mobility of surface vehicles over very wet and unstable fine-grained soils. The mechanics of the phenomenon of electroosmosis in soils are described, and the quantitative expressions for electroosmotic flow based on the theories of Helmholtz-Smoluchowski and Schmid are compared. It is apparent that the applicability of the theoretical concepts and their validity in relation to practical engineering problems remain to be established.

Based on accounts of numerous successful practical field operations, it is known that certain definite benefits are derived from the application of an electric current to wet, fine-grained soils. In addition to enhancing drainage of soils of relatively low permeabilities, the process of electroosmosis results in a consolidation of the soil that contributes to an improved strength and stability.

It has been demonstrated that an irreversible electrochemical hardening of soils containing clay occurs when aluminum electrodes are employed in the electroosmosis process. This phenomenon has resulted in the development of techniques for increasing the bearing capacity of piles, and has been explored for its possible applicability in soil reclamation and chemical injection processes.

For possible military application, electrokinetic stabilization appears to have many advantages over techniques of soil stabilization involving the use of additives, particularly for very wet soils. Its primary disadvantage appears to be the excessive length of time required to achieve stabilization. Broad areas of research are suggested that would permit an objective evaluation of electrokinetic methods for soil stabilization in military operations.

SUMMARY REVIEWS OF SOIL STABILIZATION PROCESSES

ELECTRICAL STABILIZATION OF FINE-GRAINED SOILS

PART I: INTRODUCTION

Purpose of Review

1. The search for new and more effective methods of improving the stability of natural soils led, as early as 1936, to investigations of the feasibility of soil stabilization by the application of electrical currents. Much research and many practical applications of electrical stabilization of soils have been reported since that time. The precise mechanisms involved and the manner in which many factors influence electrical stabilization, however, appear more to be theorized than established. Unless the mechanisms of such stabilization are understood in detail, little progress may be expected in field applications of this unique method of soil stabilization. The intent of this review is to summarize available information published in the technical literature concerned with the influence of an electrical current on soil properties, and to determine the practicability of electrical methods of soil stabilization in military operations, such as their possible application in stabilizing emergency military roads and airfields. It is hoped that this review will serve both to guide and to stimulate further investigations.

Scope

2. The information presented in this review has been obtained solely from material published in or translated to English. Although it is obviously not a complete survey because of this limitation, it is believed that a reasonably thorough summary of the current state of the art has been obtained. Literature from a number of scientific and engineering fields, including soil mechanics, geology, mineralogy, soil physics, and soil chemistry, has been examined for possible illuminating relations to the problem at hand. Part II herein is devoted to a brief summary of the fundamental

theory of electrokinetics in soils, to provide a basis for an understandin of the findings presented in subsequent parts. A list of all references examined is included at the end of the text.

Definitions of Terms Used

[illegible]. Certain terms frequently used in this report are defined below:

Anode. The positive pole or electrode of an electrical system.

Cathode. The negative pole or electrode of an electrical system.

Electrokinetic phenomenon. The process by which a phase (i.e. liqui or solid) is displaced mechanically along the boundary of another phase accompanied by a coexisting electromotive force.

Electroosmosis. The movement of an aqueous solution through a porou material under the influence of an externally applied electromotive force.

Electrophoresis. The movement of particles of a solid through an aqueous solution under the influence of an externally applied electromotiv force.

Streaming potential. The electromotive force created by the movemen of an aqueous solution through a porous material.

Sedimentation potential. The electromotive force created by the mov ment of particles of a solid through an aqueous solution.

Thermodynamic potential. The total drop in potential between the liquid and solid phases.

Zeta potential (electrokinetic potential). A part of the thermodynamic potential representing only the potential difference between the strongly adsorbed liquid layer on the solid and the interior of the solution.

PART II: THEORY OF ELECTROKINETICS IN SOILS

4. Before an evaluation of electrical stabilization methods can be made, it is believed desirable to review briefly the basic electrokinetic concepts. A brief description of the history and evolution of several concepts is therefore offered in the following paragraphs.

Early Observations

5. In 1809, Reuss reported the results of several experiments in which he observed the first of four primary processes which have since been termed the "electrokinetic phenomena." He noted that when a direct current potential was placed across a clay or fine quartz layer, water migrated toward the negative pole. It was later found that clay particles suspended in water carried a negative charge, and thus were drawn toward the anode in an electric field. These processes have been termed "electro-osmosis" and "electrophoresis," respectively. It was evident that they were dependent upon some charge differential which existed at the interfaces of a solid-liquid system.

6. Since it was established that the application of a current through a solid-liquid system caused a movement of each phase to one of the electrodes, it might be anticipated that a reverse effect would also exist. That is, the movement of either phase relative to the other should produce an electric potential. In 1859, Quincke noted that a potential difference existed across a diaphragm through which a liquid flowed under hydrostatic pressure. This potential was termed "streeming potential" and is the converse effect of the electroosmosis process. Somewhat later (1878), Dorn conducted tests in which a potential was observed as a result of movement of solids in suspension. This potential, representing the converse effect of electrophoresis, has been termed "sedimentation potential." Investigations of the electrokinetic processes during the period from 1809 to 1879 thus were devoted primarily to the recognition of the phenomena, their classification, and attempts to derive empirical expressions for their explanation.

Double Layer Theory

7. In 1879, Helmholtz presented an analysis of electroosmosis based on the electric "double layer" concept. This provided the first rational approach to the explanation of electrokinetic phenomena in terms of the fundamental equations of electrostatics and hydrodynamics. The theoretical treatment by Helmholtz was based on the assumption that, in the two-phase solid-liquid system, a layer of ions exists at the solid surface which is countered by a rigidly held parallel layer of opposite charges in the adjacent liquid. A simple illustration of the Helmholtz double layer system is given in fig. 1. It should be noted that, although the negative charges are shown to be in the liquid phase of the system, these ions are adsorbed by the solid structure and rigidly held thereto by coulombic forces. By considering that the oppositely charged layers are at molecular distances from each other, the system may be treated mathematically as a simple parallel-plate condenser and the electrical potential difference, ΔP, across the double layer may be determined by the expression:

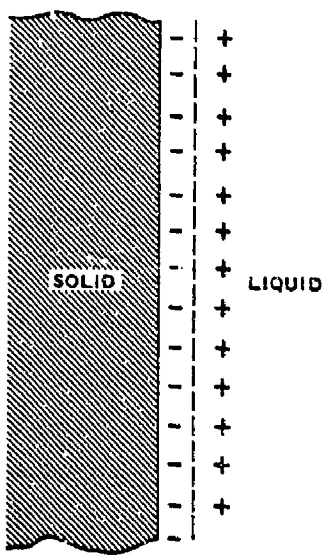


Fig. 1. Model of the Helmholtz double layer

$$\Delta P = \frac{4\pi ed}{D}$$

where all dimensions are in centimeters and electrostatic units and

e = charge per unit area

d = distance between parallel plates

D = dielectric constant of material between plates

8. Although the Helmholtz theory of the double layer provided a quantitative explanation of electrokinetic phenomena, later considerations indicated that the concept of the rigid array of charges at the interface was inadequate. A more reasonable structure was the "diffuse double layer" proposed by Gouy and extended later by Stern and others. According to this concept, the double layer is composed of two layers: (a) an inner, fixed layer consisting primarily of ions adsorbed by the solid surface along with a tightly held layer of the adjacent liquid, and (b) an outer, mobile layer

consisting predominantly of the countercharges necessary to electrically balance the fixed layer. A model of the diffuse double layer is shown in fig. 2. In reality, there is an atmosphere of both positive and negative charges in the two layers, but for practical purposes it will be sufficient to consider the fixed layer as negative and the mobile portion of the double layer as positive.

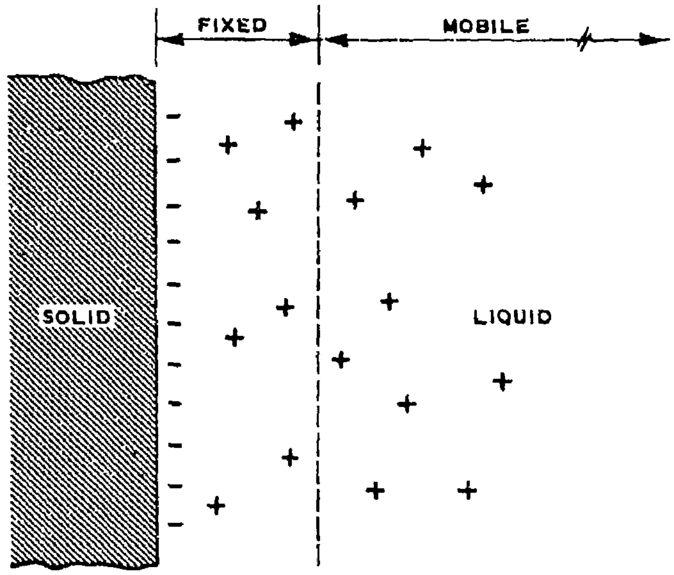


Fig. 2. Model of the diffuse double layer

9. In the diffuse double layer concept, two primary potential drops are recognized. The first, or "thermodynamic" potential, is the total potential difference between the actual solid phase and liquid phase outside the zone of the diffuse layer. Thus, the thermodynamic potential is the maximum potential difference that exists in a solid-liquid system. The second potential, termed the "zeta" (or frequently referred to as the "electrokinetic") potential, is the difference in potential between the fixed portion of the diffuse layer and the liquid outside the diffuse layer. A typical distance-potential relation, showing the thermodynamic and zeta potentials, is given in fig. 3.

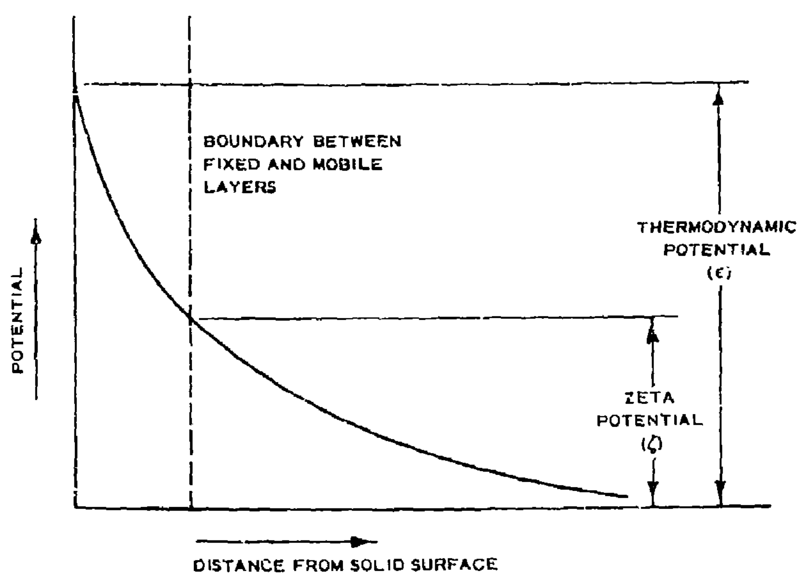


Fig. 3. Distance-potential relation for solid and liquid in contact

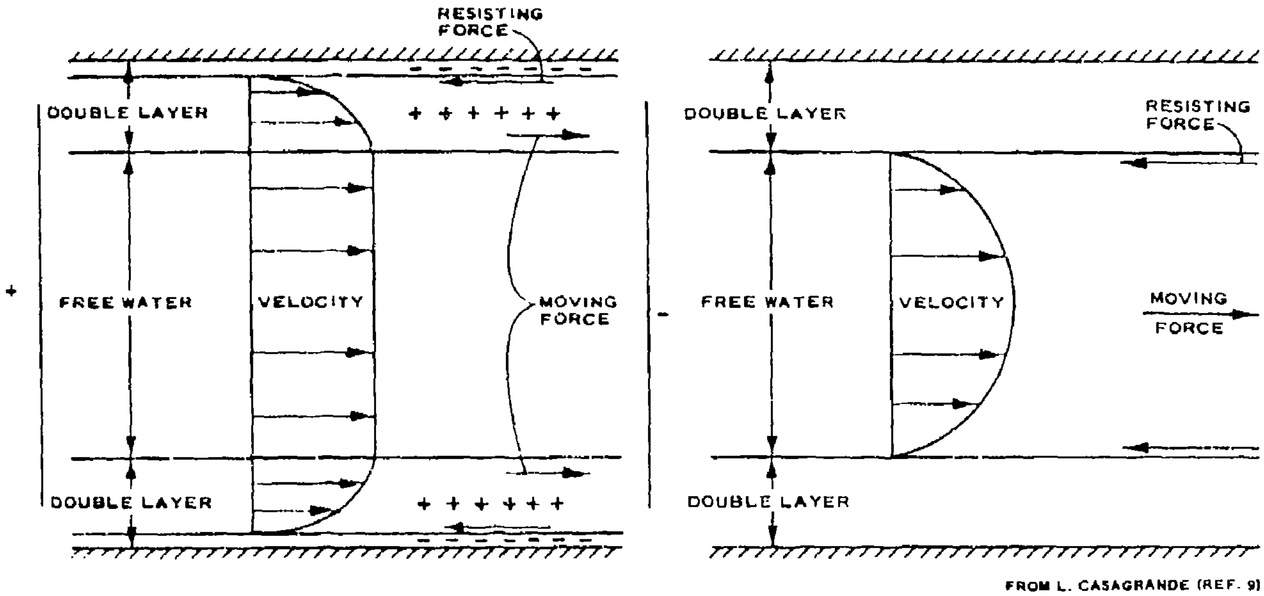
10. Using the plate condenser assumption of Helmholtz, the basic mathematical expression of the zeta potential is the same as that given in paragraph 7. Quantitatively, the zeta potential is dependent upon the combined influence of several complex and

generally interrelated factors. Among the more important factors are: (a) the composition of the solid phase, (b) the nature of the liquid phase, (c) the concentration of electrolytes in the liquid, (d) the valence and nature of the ions forming the double layer, (e) the strength of the electrostatic forces, and (f) the temperature of the solid-liquid system. Although a detailed discussion of these factors is beyond the scope of this review, the existence of these variables and the manner in which they are related must be considered in any study of electrokinetic phenomena. These considerations are particularly important in avoiding misinterpretation of the zeta potential, since it cannot be measured directly but must be deduced from carefully controlled experiments and observations during an electrokinetic process.

The Electroosmotic Phenomenon in Soils

11. When a direct current is applied by means of embedded electrodes to a saturated fine-grained soil, a migration of the pore water to the cathode generally will occur. The mechanics of this phenomenon, electroosmosis, as described by Leo Casagrande,[9*] are summarized here briefly with the aid of fig. 4a. This treatment is based on the assumptions that the saturated pores are water-filled capillaries, that the pore width is large compared with the thickness of the double layer, and that the principles of the Helmholtz flat-plate condenser concept are applicable. Consider a capillary tube filled with water with an electrical current flowing from the anode to the cathode. The charged layers at the wall of the capillary (the double layer) are treated as the plates of a condenser, the difference in potential between the plates being the zeta potential. Outside the zone of the double layer boundary, the capillary contains free water which is able to move under the influence of a hydraulic gradient. When an external electrical field is applied to this system, a displacement force is established in the double layer which causes a migration of ions in the thicker, mobile portion of the double layer to the oppositely charged electrodes. In soils, this is predominantly a movement of positive charges toward the negative electrode; however, in rare cases, a net negative

* Raised numerals refer to similarly numbered items in the list of references at end of text.



a. Electroosmotic flow b. Hydraulic flow

Fig. 4. Velocity distribution in electroosmotic and hydraulic flow

charge may exist in the mobile part of the double layer that will result in a migration toward the anode. In this migration toward the electrode, frictional forces are developed which "drag" along the water molecules in the movable portion of the double layer. These forces are transmitted also to the free water inside the capillary cylinder which, assuming no external hydraulic gradient, causes a movement of this water in the same direction. When the electrical forces and frictional forces are balanced, a steady-state volume flow of water occurs. The velocity distribution of electroosmotic flow is shown in fig. 4a. Examination of figs. 4a and 4b shows a comparison of electroosmotic flow with ordinary flow due to a hydraulic gradient. As shown, the hydraulic flow of water through fine capillaries is laminar, with, for all practical considerations, a zero velocity at the boundary between the free water and the double layer.

Helmholtz-Smoluchowski Theory

12. Equations for quantitatively expressing the electroosmotic phenomenon described above were derived by Smoluchowski in his extension to porous systems of the basic Helmholtz electrokinetic concepts. From a consideration of the assumptions of the basic Helmholtz-Smoluchowski

theory, the following expression for electroosmotic flow through a capillary has been developed:

$$q_e = \frac{D\zeta aE}{4\eta\pi L} \qquad (1)$$

where all dimensions are in cm-g-sec system and electrostatic units and

q_e = volume of liquid moved per unit time
D = dielectric constant of liquid in the double layer
ζ = electrokinetic (zeta) potential of the double layer
a = cross-sectional area of the capillary
E = electrical potential between electrodes in volts
η = viscosity of the liquid
L = distance between electrodes

By substituting i_e (the potential gradient) for $\frac{E}{L}$ and c_1 (a constant) for $\frac{D\zeta}{4\eta\pi}$, equation 1 may be written as

$$q_e = c_1 \cdot i_e \cdot a \qquad (2)$$

or in terms of the velocity of flow per unit time as

$$v_e = c_1 \cdot i_e \qquad (3)$$

Extension of equations 2 and 3 to a porous system, such as soil, containing many capillaries over a given cross-sectional area results in expressions for quantity and velocity of electroosmotic flow in terms of the porosity, or void ratio, of the system. Thus, for a soil mass of porosity n (or void ratio e) and total cross-sectional area A, the total volume of liquid transported per unit time during electroosmosis may be determined from

$$Q_e = k_e \cdot i_e \cdot A \qquad (4)$$

and velocity of flow per unit time may be determined from

$$v_e = k_e \cdot i_e \qquad (5)$$

where

$$k_e = n \cdot c_1 \text{ , or } \frac{e}{1 + e} \cdot c_1$$

The quantity k_e is called the electroosmotic coefficient of permeability (or, less frequently, the electroosmotic transmission constant). It represents the volume of liquid moved per unit time through a unit area of soil under a potential gradient of 1 volt per unit length. In the cm-g-sec system, k_e has the dimensions square centimeters per second-volt, which is more easily visualized as centimeters per second for a potential gradient of 1 volt per cm.

13. Equation 5 for electroosmotic flow is directly analogous to hydraulic flow as defined by Darcy's law and the corresponding equation

$$v_h = k_h \cdot i_h \qquad (6)$$

where

k_h = hydraulic coefficient of permeability in centimeters per second

i_h = hydraulic gradient

Further, from the basic Poiseuille equation governing laminar flow, it can be shown that

$$k_h = a \cdot n \cdot c_2 \quad \text{or} \quad a \cdot \frac{e}{1 + e} \cdot c_2$$

where

a = cross-sectional area of an individual capillary in square centimeters

c_2 = a constant dependent upon properties of the liquid

Thus, it is evident that the hydraulic coefficient of permeability and, therefore the velocity of flow are proportional to the area of the capillaries. On the other hand, in electroosmotic flow, the coefficient k_e and the velocity of flow are independent of the size of the capillaries.[9]

Schmid Theory

14. In 1951, Schmid presented a theory of electroosmotic flow based on a simplification of the distribution of ions in the double layer.[4] The

theory is claimed to be of particular value in regard to flow in microporous systems such as fine membranes, ultrafilters, adsorbents, and lacquer films, where the assumption in the Helmholtz-Smoluchowski theory of small double layer thickness in relation to total pore diameter becomes untenable.[52] The Schmid calculations are based on the assumptions that the pore diameter is small in comparison with the thickness of the double layer, and that the counterions are uniformly distributed throughout the entire liquid volume. Thus, the applied electric potential would act on all the counterions rather than only on those attached to the double layer as in the Helmholtz-Smoluchowski concept. The basic equation derived by Schmid is[4]

$$p_e = F\psi E \tag{7}$$

where

p_e = electroosmotic equilibrium head in centimeters of water
F = the Faraday constant (9.65×10^4 coulombs)
ψ = the adsorbed ion concentration (or concentration of wall charges) in gram-equivalents per liter of pore liquid
E = the applied potential in volts

15. From the fundamental Schmid equations, Winterkorn[52] has derived the following equation

$$q_e = \frac{\pi r^4}{8\eta} \cdot B \cdot F \cdot a \cdot i_e \tag{8}$$

where

q_e, η, a, i_e, and F are as defined previously
B = concentration of wall charges in ionic equivalents per unit volume of pore liquid

The total flow volume per unit time over a porous system of area A and porosity n becomes

$$Q_e = \frac{\pi r^4}{8\eta} \cdot B \cdot F \cdot n \cdot i_e \cdot A \tag{9}$$

This equation can be expressed in the form of equation 4 where the coefficient of electroosmotic permeability is represented by

$$k_e = \frac{\pi r^4}{8\eta} \cdot B \cdot F \cdot n$$

which is further reduced by Winterkorn[52] to the form

$$k_e = C(1 - n)^{2/3} n^3$$

where

C = a soil constant that varies with temperature

As expressed above, the value of k_e is a logarithmic function of the porosity and is dependent upon the radius of the capillary. By contrast, the value of k_e in the Helmholtz-Smoluchowski derivation is directly proportional to the porosity and is independent of the radius of the capillary.

Theory Comparisons

16. In comparing the general aspects of the theories of electro-osmosis described, it is apparent that the major characteristic quantity of the Helmholtz-Smoluchowski theory is the zeta potential, whereas the ion concentration in the pore fluid is the important characteristic of the Schmid theory. Inasmuch as the zeta potential quantity must be determined from measurements of electroosmotic flow or streaming potential tests, an advantage is claimed for the Schmid theory in that the ion concentration can conceivably be determined by a direct method such as ion exchange.[16] Perhaps equally as important, both theories depend upon assumed values for the dielectric constant and the viscosity of the pore fluid, which often may be a source of significant error.

17. Winterkorn[52] presented experimental evidence to compare and determine the validity of both theories. An electroosmosis apparatus was employed that was designed to permit the measurement of the electro-osmotic coefficient of permeability k_e at various porosities n which were kept constant throughout each test. From the results of tests on a kaolinite and a bentonite, it was concluded that the relation between k_e and n is in agreement with the Schmid theory and in contradiction to the Helmholtz theory. It was recognized, also, that the Schmid concept does

not take into account the hydration of the clay particles and their exchange ions, and that consequently the Schmid concept must be modified to include the swelling characteristics of the clay system.

18. Casagrande,[10] in commenting on the work of Winterkorn, states that the results cannot be used to prove or disprove the Schmid theory because (a) gas formations at the electrodes so greatly influence the velocity measurements that the quantitative results are useless as a basis for checking theories, and (b) soil samples shrink irregularly during electroosmosis and therefore a constant porosity of the sample cannot be maintained. He further states that some of the relations determined may be explained by the fact that, with increasing porosity, the increased mobility of individual particles leads to electrophoresis with a resultant decrease in electroosmotic flow.

19. Bolt,[4] by consideration of average values of pore diameter, thickness of double layer, and distance between charges on the solid surface, reasons that the application of the Schmid equation for a typical heavy clay soil would be valid only if the moisture content of the soil was 5% or less. On this basis, he concludes that the Schmid concept of electroosmosis for the specific case of soils is unsatisfactory. This contention was supported by experiments by Harvard University[16] on various clay systems which showed that the observed variations of electroosmotic flow with permeability and porosity were compatible with the predictions based on the Helmholtz-Smoluchowski equations and in no way supported the applicability of the Schmid equations to these systems.

20. It is likely that neither of the two major theories of electroosmosis is exact, but that they represent only an orderly and simplified presentation of an extremely complex problem. This becomes more apparent with the realization that highly complicated changes occur within a system itself during the electroosmotic process, and none of the presently employed philosophies can predict these alterations with certainty. Application of these theoretical tools, however, in combination with experience and increased knowledge of soil-water systems has resulted in greater confidence in the designs and practical utility of electroosmosis equipment and techniques in field engineering problems.

PART III: EFFECTS OF ELECTROOSMOSIS

21. Although extensive industrial applications of the electrokinetic phenomena have been made since the turn of the century, only since about 1930 have these processes been considered as a means of treating soils for engineering purposes. The development of practical electroosmotic stabilization methods for soils is attributed primarily to the efforts of Leo Casagrande. Since the time of these pioneer efforts, the versatility and desirability of electroosmotic stabilization for practical field application have been increasingly recognized. The most common use of the method has been for the stabilization of steep slopes created by excavation in wet, fine-grained soils. The fundamental technique of electroosmosis consists of connecting a source of direct current to a series of metal electrodes which are embedded in a saturated soil. The current will cause the pore water to flow toward one of the electrodes, in most cases toward the cathode. A phenomenon of base exchange may also occur during the process in which the ions attached to the surface of clay minerals will be exchanged with other ions of like polarity that are present in the pore water or that are carried in by the electric current.

Electroosmotic Dewatering

22. The primary effect of passing a current through a wet soil is the dewatering or drying of the mass. Most fine-grained, clay soils are stable at low water contents, but become increasingly fluid and less stable as the water content increases. Because of the relatively low permeabilities of clay soils, drainage by normal gravity flow often cannot be accomplished and electroosmosis becomes of value. The reduction of water content by only a slight amount, accompanied generally by other changes in the soil structure, can be sufficient to produce the required soil stability. Since natural clay particles have an effective net negative charge, an electroosmotic flow will occur from the anode to the cathode when a direct current is applied through the soil mass. Thus, the soil water content will decrease at the anode and increase at the cathode. The water accumulated at the cathode may be disposed of by

installing a well-system cathode with a pump discharge.

23. According to the relations described earlier, the electro-osmotic flow velocity at any point in a soil mass is proportional to the electric potential gradient at that point. The potential gradient depends upon the total available potential difference and the electrode configuration, and may be determined at any point between the electrodes from a developed flow net. For a particular total potential difference, the flow net is a function of the size, shape, and spacing of the electrodes. In most cases, a natural hydraulic flow will exist in a soil mass, which may either oppose or aid electroosmotic flow. Schaad and Haefeli[37] have extended the electroosmotic flow equations for porous materials to include the combined influence of hydraulic and electrokinetic actions. The field design and capabilities of an electroosmotic flow system may be determined by hydraulic or electric analog model studies. Normally, this requires knowledge of the existing hydraulic flow net, establishment of the hydraulic flow boundary conditions in a model, and determinations of the contribution of electroosmotic drainage designs to the resultant flows.

24. The significance of the effect of electroosmosis on the draining of soils, particularly silts and clays of low natural permeabilities, has been aptly described by Casagrande.[7,8,9] From studies of a wide variety of soils, it has been observed that the coefficient of electro-osmotic permeability is relatively independent of the soil type and its characteristic hydraulic permeability. Casagrande considers that, for all practical purposes, an average coefficient of electroosmotic permeability of 0.5×10^{-4} cm per sec for a potential gradient of 1 volt per cm may be assumed for most saturated fine-grained soils. Where greater precision is required, however, caution must be exercised in assigning a value for the electroosmotic permeability since it is dependent upon the zeta potential, which varies with the nature of the solid-liquid interface and is influenced by the type of adsorbed counterions and electrolyte concentration.[16,27] Similarly, for nonsaturated soil conditions, the coefficient varies with the moisture content or porosity of the soil.[50,52] In any event, it becomes apparent that a soil of extremely low natural permeability would be benefited significantly by the increased permeability afforded by electroosmosis. With soils of greater natural permeability, the

advantage of electroosmotic drainage becomes proportionally less. It should be mentioned that, although the electroosmotic permeabilities of soils may be nearly identical, the conductivity of the soils is not necessarily the same. Thus, the required electrical energy for electroosmotic drainage may differ appreciably for different soils even though the quantity of water moved by electroosmosis may be the same. In general, the amount of electricity required to move a given unit quantity of water increases with increasing soil surface area (i.e. decreasing particle size).[8,44]

Electroosmotic Consolidation

25. In addition to the removal of water, the process of electroosmosis causes consolidation of the soil. The decrease in volume of a compressible soil during electroosmosis contributes significantly to the increase in strength and improved stability of the soil. It is believed that much of the success of electroosmosis in practical field installations is due to this attendant effect. Although consolidation of a soil by electroosmosis is an established fact based on observations made in the field and laboratory by numerous investigators, much work still is needed to provide a better understanding and working concept of this phenomenon.[9,10,12,14,25,30,37,48] In most of the consolidation studies, it was generally determined that the effect of electroosmosis was similar to providing an additional load to an existing static load in the consolidation theory. As described by Casagrande,[8] observed settlements of the ground surface in the areas of the electrodes were larger than could be accounted for by the development of negative stresses in the pore water. Laboratory model tests showed that without surcharge, practically no volume decrease occurred during electroosmosis. When the soil specimens were surcharged, however, appreciable volume decrease occurred. Preece,[30] by alternately applying static loads and potential, showed that consolidation under additional equal increments of static load is materially decreased after electroosmotic treatment. From comparisons of electroosmotic loading with normal static loading consolidation curves, he suggests that electroosmosis produces a stabilizing effect distinct from the increase in stability due to consolidation alone. Vey[48] developed

expressions for quantitative determination of the effects of electroosmosis on consolidation. He further states that the effective load increase, representing the electroosmotic pressure, acts both by removing moisture from the pores and by creating pore water tensions which ultimately become balanced by intergranular pressures developed upon consolidation.

26. Casagrande[9] has described the phenomenon of consolidation of compressible soils by electroosmosis in terms of the stresses developed in the pore liquid and the walls of the capillaries. The existence of these stresses, their distribution, and their contribution to increased strength and stability of soils subjected to electroosmosis have been examined extensively in a series of investigations conducted by Harvard University for the Navy Department.[15,16,17] That these forces play an important role in the electroosmotic processes appears to be an established fact, but it is believed that much additional work is required to establish their full significance.

Field Applications

Examples

27. The first successful application of electroosmosis for controlling unstable soil conditions was made in 1939, in an excavation of a long railroad cut in Germany, under the direction of Casagrande.[9] Extensive flow slides of a saturated clayey silt at a shallow excavation depth had impeded construction progress. In a 300-ft-long trial section, perforated steel pipe cathodes were spaced at 30-ft intervals along the top and sides of the excavation and driven to a depth of 22.5 ft. Pipe anodes were placed midway between the cathodes, and a potential of 180 volts (later decreased to 90 volts) was applied to the system. Within a few hours, the stability of the slopes had improved sufficiently to permit further excavation. Total consumption of energy amounted to about 1 kwhr per cu yd of excavation.

28. Based on the encouraging results of this successful trial of electroosmosis technique, the method was extended to other construction problems by Casagrande and others. The majority of work of this type has been done in European countries. Special applications include, in addition

to improving the stability of slopes, the stabilization of vertical soil walls and trenches, stabilization of tunnel excavations, decreasing the water contents of industrial wastes, and increasing the bearing capacities of friction piles.[9,10,22,24,30,32,44] Detailed accounts of these applications are repeated throughout the literature and will not be given herein. In most cases the ultimate purpose of the electroosmosis was to increase stability by water removal. It has been demonstrated repeatedly that a large reduction in water content is not required to effect a significant improvement in strength and stability. Reductions in moisture content of as little as 1 to 3% have been shown to more than double the strength properties of soils. Also, certain situations are recorded wherein moisture contents were reduced negligibly, but stability was improved by merely changing the direction of hydraulic flow away from the critical area and reducing the hydrostatic pressures involved.

Equipment

29. Field installations for electroosmotic drainage are basically simple and inexpensive. Ordinary steel pipe, drilled to provide water exits, serves conveniently as cathodes. If a more refined drainage system is desired, wellpoints may be used. Anodes may consist of any type of scrap iron, such as rails or pipes, and in certain applications, sheet piling at the faces of cuts may constitute the anode. The anodes corrode rather severely during electroosmosis, but the cathodes do not corrode and may be salvaged for re-use. Spacing of electrodes between 12 and 16 ft apart, with potentials varying between 30 and 180 volts, has proved to be effective and economical according to Casagrande. For long-term application, a potential gradient of from 1 to 2 volts per cm during the first few hours is desirable to cause a more rapid build-up of tension in the pore water, with the potential gradient reduced thereafter to a value no greater than about 1/2 volt per cm. Methods have been presented to provide estimates of electrical current requirements for electroosmosis in the field.[8,31,47] Because electroosmotic stabilization appears to be reasonably permanent, the power supply may be interrupted periodically without harmful effects. The feasibility of intermittent electroosmotic operation, with the resulting savings in power and cost, has been studied by the Bureau of Reclamation.[46]

PART IV: ELECTROCHEMICAL STABILIZATION

30. Electrochemical hardening of the soil may take place by the deposition of decomposed metal salts in the soil pores. It may also occur if these salts react with free agents present in the pore water or on the surface of the soil particles. Practically all attempts to utilize electrochemical hardening appear to have been in the realm of pile stabilization rather than stabilization of large soil masses. The results of such tests indicate that hardening occurs only in the immediate vicinity (10 to 14 in.) of the electrodes. Thus, it appears that in order to use electrochemical hardening for stabilization of large masses, present procedures must be improved.

31. Casagrande[6] has reported that all clay-containing soils are capable of electrochemical hardening. It is generally agreed that only aluminum electrodes produce permanent, irreversible electrochemical hardening and that even introduction of aluminum salts results in a temporary stabilization only.[6,14,20,21,26,38,40,53]

Piles

32. In 1930, Casagrande[8] discovered that electroosmosis combined with aluminum anodes results in an irreversible hardening of clays. All metal anodes tested other than aluminum produced only a temporary hardening of the clay which was lost when the soil was slaked in water for a short time. On the other hand, soils treated in conjunction with aluminum electrodes retained their strength during a three-year slaking period.[40] Evidence of strong corrosion of aluminum electrodes has been noted in all cases, particularly the anode. This, plus the presence of insoluble salt deposits in the soil adjacent to the electrodes, indicates that physical decomposition of the electrodes takes place.

33. On the basis of favorable model test results, Casagrande[6] conducted a full-scale test in 1937. Six 1-ft-diameter wooden piles, sheathed with aluminum, were driven to a depth of about 20 ft. The bearing capacity of the piles was found to be 7 to 9 tons per pile before treatment. A potential of 220 volts, which resulted in 40 to 60 amp of current,

was applied to the piles in various combinations. Intermittent loading tests showed that the piles reached a maximum bearing capacity of about 40 tons per pile after about 30 kwhr of energy had been consumed, and that further treatment resulted in decreased bearing capacity. This apparent optimum amount of treatment was later confirmed by laboratory experiments. Withdrawal of the piles upon completion of the tests showed that soil had become firmly bonded to the aluminum sheaths and that the soil between the electrodes was apparently unaltered.

34. Spangler and King[40] conducted model pile studies in an attempt to explain the above-mentioned optimum treatment phenomenon. They attributed the ultimate decrease in bearing capacity to a gradual reduction in the skin friction due to the increased amounts of powdery salts deposited around the electrodes. It is obvious that pile foundations are particularly adaptable to electrochemical stabilization since the piles may be used as electrodes.

Electrochemical Injection

35. An intriguing possibility is the use of electricity to increase the speed of a chemical reaction in soil to be stabilized or to furnish additional ions to assist in the occurrence of the base exchange phenomenon. Casagrande[10] has stated that the base exchange process is very slow, and that in clays the spreading rate of base exchange decreases with the distance from the electrodes. Thus, it is probable that in practical applications the strength increase as a result of base exchange will not be of major importance.

36. The use of electrical treatment of soil for reclaiming alkali and saline-alkali soils has been investigated by the U. S. Bureau of Reclamation.[47] A model tank was filled with highly saline-alkaline soil to which leaching and electrical treatment were applied under controlled conditions similar to possible field applications. The soil and water were sampled periodically, and systematic tests were conducted on these samples to determine the changes in characteristics resulting from electrical treatment in relation to those resulting from leaching treatment without electricity. These tests showed that electrical treatment alone cannot be

considered a complete process of alkali soil reclamation. Salts, principally those of sodium, exist in alkali soils in large quantities. There must be some means of carrying them off, and electricity alone does not adequately supply this means although it does assist in moving the salts from anode to cathode. Adequate leaching and drainage may supply this means. The favorable effects of electrical treatment are those causing desirable reactions in the soil which leaching without electricity does not achieve. The aim of past research on improving the stability of alkali soils has been to cause similar desirable reactions, such as by chemical amendment, to assist the effectiveness of leaching and drainage. The results of these tests show that electrical treatment causes these desirable reactions to occur, and thereby boosts the rate and potential quantity of ionic base exchange reactions. The actual quantitative value of strength increase due to ionic base exchange remains to be investigated.

37. Electrochemical injection could possibly be used in certain heavy soils of such low permeability that mechanical pressure injection or grouting processes would be unsatisfactory. This method seems particularly desirable since the direction and extent of fluid penetration may be closely controlled by the electrode spacing and configuration. Very few actual tests of electrochemical injection techniques are reported in available literature;[20,35] however, it has been stated[37] that the object of such injection is to form stable combinations, such as occur in nature, by the use of cheap, soluble salts. It is suggested that certain liquid resins, as well as silicate solutions, might be examined as possible satisfactory electrochemical injection materials.

PART V: DISCUSSION AND SUGGESTIONS FOR NEEDED RESEARCH

Applicability for Military Soil Stabilization

Soil stabilization problem and requirements

38. Based on the preceding review, it is possible to make certain statements about the specific advantages or limitations of electrokinetic methods, particularly with reference to the usefulness of these techniques for military soil stabilization applications. One of the major objectives of the present military soil stabilization research program is to develop materials or methods capable of strengthening soils for use in emergency road and airfield construction to improve the mobility of the military forces. The general approach employed to date has involved the in-place treatment of soils, particularly the water-susceptible clay and silt types, to provide a sufficiently firm soil surface layer of finite depth capable of supporting traffic of specified loads and frequencies. Where areas of soils having moderate initial stability are encountered, the application of chemical soil stabilizers appears to afford a logical solution. However, it is anticipated that areas of excessively wet soils, with practically no initial stability, will also be encountered. It is particularly for this very wet soil condition that electrokinetic techniques are being considered as possible solutions to the stabilization problem.

39. In terms of specific requirements, a stabilization method or process is desired that is relatively simple in operation and nonhazardous to operating personnel. Required equipment should be reasonably portable and, if possible, capable of being re-used. The stabilizing method must be able to achieve the desired degree of stability within a short period of time. Although it is desired in most instances that the stabilization achieved be reasonably permanent and resistant to adverse weather conditions, certain military operations require the passage of only a relatively small number of supporting vehicles for only a short period of time. In these cases, permanency of stabilization would not be necessary. Perhaps the most important requirement to be satisfied is that of obtaining sufficient strength in the stabilized soil layer to enable it to withstand the

applied loads. For a soil having a water content near saturation, this demands an improvement in strength from a condition of practically no stability to one of an estimated 4 to 5 CBR bearing strength. This is roughly equivalent to an unconfined compressive strength of 25 to 30 psi. A soil of this strength will normally tolerate the passage of about 40 to 50 cargo-truck type vehicles, but with progressively increasing rut depths.

Advantages and limitations

40. Upon consideration of the above requirements, electrokinetic stabilization methods appear to have several advantages over techniques of stabilization involving the use of additives to harden very wet soils. The equipment required to accomplish electrokinetic stabilization is not complex, and consists of components which are readily transportable by existing military vehicles. These include items such as gasoline-powered generators, wiring, metal electrodes, and possibly a simple pumping system to assist in the removal of water accumulated in the vicinity of the cathodes. Once the equipment has been installed, the process would proceed with minimum surveillance and attendance by operating personnel. With the exception of possible deterioration or inability to salvage the easily replaceable electrodes, the equipment involved can be utilized over and over again. Of primary benefit is the fact that electrokinetic methods do not require construction operations such as in-place mixing of additives and compaction which are virtually impossible to accomplish with existing field construction equipment on very soft and unstable soil. In addition, the depth of required stabilization does not constitute a problem when electrokinetic treatment is employed.

41. The applicability of electrokinetic stabilization for military purposes is limited to a considerable extent by the rather long periods of time required to achieve substantial changes in soil stability. With reference to the electroosmotic or dewatering process, several days may be involved in the operation. However, before the time limitation is considered to be a severe disadvantage, a more thorough understanding of the early effects of electrical treatment is desirable. Thus, the time deficiency problem may, in reality, be one of the degree of effectiveness that is attainable in a given situation, or it may be susceptible to circumvention or improvement by specially designed techniques. For

example, it has been shown that pieces of metal placed between the active electrodes behave as if they were actually in the circuit. Thus, it might be possible to achieve the benefits of very close electrode spacing without a complex maze of wiring. By incorporating metal sheets or mesh for this purpose, it is possible that stabilization could be accomplished more rapidly.

42. Even if the time requirement imposes a real limitation, the possible utility of electrokinetic methods for military stabilization is not necessarily eliminated. There are situations in which the time factor may not be critical. For example, advanced planning may permit the stabilizing of areas such as supplementary bridge approaches and roads or missile-launching sites well ahead of the actual military need.

43. The extent of strength development that can be accomplished by electrokinetic stabilization is dependent upon the particular surface condition encountered. Successful field application has demonstrated that soils respond to electrical treatment in a complex manner. The removal of water is generally accompanied by significant consolidation of the soil while, at the same time, irreversible reactions or alterations of the chemistry of the soil itself may take place. The ultimate strength development resulting from these interrelated effects cannot be predicted on the basis of existing knowledge. In several instances, strength increases have been reported that cannot be explained solely on the basis of water removal and consolidation during electrical treatment. It is not improbable that electrokinetic stabilization could result in improved bearing strengths that would satisfy the requirements for limited traffic operations. Perhaps it would be of even greater benefit in increasing strength if electrical drainage were accompanied by periodic applications of additional consolidation loads such as mechanical compaction. Even assuming that only a modest improvement in bearing strength can be achieved electrokinetically, the severity of the initial soil condition would be lessened, suggesting the possibility of a more effective follow-up stabilization involving the use of additives. Although no reports of studies of this approach have been found, the use of electrical energy to assist in the distribution and incorporation of stabilizing additives and to aid the reaction processes is an interesting possibility.

44. Another suggested application of electrokinetic stabilization might involve the use of prefabricated metal landing mat surfacing as the anode with a series of cathodes embedded alongside or, perhaps, buried horizontally at some depth beneath the surface. Thus, it might be possible to improve the bearing capacity of the soil under the metal mat, which would increase the mat-carrying ability or reduce the specified requirements of the metal mat itself.

Suggestions for Needed Research

45. All of the preceding suggested applications of electrokinetic stabilization represent unique and untested approaches to the problem of improving the mobility of the military forces. Based on the review of previous work and investigations performed to date, it is apparent that much remains to be learned about the science of stabilization by electrical treatment. Primarily as a result of the efforts of relatively few investigators new dimensions have been added to a science still in its infancy. Although demonstrated by several successful field applications to be technically sound and economically feasible for certain situations, electrokinetic stabilization methods are frequently overlooked or rejected in favor of more time-tested techniques. Consequently, it is virtually impossible to predict with certainty whether electrokinetic methods are capable of satisfying even a portion of the problems of military soil stabilization, since no major effort has ever been expended with this specific application in mind. Thus, it becomes apparent that an objective appraisal of electrokinetic techniques for military stabilization purposes can be made only from investigation of these methods both in the laboratory and in the field. In view of this, generalized suggestions are offered concerning areas of research that might provide a basis for a program to determine the full potential of electrical treatment for military soil stabilization purposes.

46. Although theories such as those of Helmholtz or Schmid are available to describe quantitatively the phenomenon of electroosmotic flow, their verification and applicability to specific field engineering problems remain to be established. These concepts are, to a large extent, dependent

upon knowledge of factors that must be estimated or derived indirectly, often with sufficient error to cause misinterpretation of results. Because of this, it is suggested that perhaps a more suitable approach might be to attempt to derive empirical relations, within the framework of the existing theories, to afford quantitative expressions for electroosmosis. It is possible that simplified relations may be determined, applicable only to specific situations, that are expressible in terms of soil parameters that can be measured directly both in the laboratory and in the field.

47. Equally important and necessary are studies to clarify the mechanics and contributions of the electrokinetic phenomena to the development of strength or improved bearing capacity of soils. In this regard, the influence of soil characteristics, both physical and chemical, must be considered in terms of their response to electrical treatment. Knowledge of the contribution of ion exchange reactions, or perhaps the effect of processes involving the incorporation of supplementary cementing materials, in the improvement of soil stability would be desirable. The influence of time must be considered, and studies must be conducted to attempt to improve the rates at which stabilization can be accomplished electrically. In this respect, the effects of variables relating to the processes themselves, such as electrode types, spacings, and shapes, as well as power input and operational methods, should be determined. The possible benefit of supplementary consolidation to implement strength improvement also demands consideration.

48. A test program incorporating the above-suggested areas of research would have as its primary objective the determination of the maximum capability of electrokinetic methods to satisfy a specific military soil stabilization problem. Only by undertaking such a program can the techniques be evaluated and their full potential for the military be established beyond speculation.

REFERENCES

1. Abramson, H. A., "Electrokinetic phenomena." American Chemical Society Series (1934).

2. Barber, E. S., "Electrical stabilization of soil." Roads and Streets, vol 91, No. 6 (June 1948), pp 64-65.

3. Begeman, H. K. S., "The influence of a direct current potential on the adhesion between clay and metal objects." Proceedings, 3rd International Conference on Soil Mechanics and Foundation Engineering, vol I (1953).

4. Bolt, G. H., Review of Theories Relating to Electro-osmotic Stabilization of Soils. ASTIA 88053, April 1955.

5. Boyer, W. C., Hart, E. G., and Konder, R. L., Studies of the Stabilization of Swamp Deposits. The Johns Hopkins University, Technical Report No. 8, June 1956.

6. Casagrande, L., "Electrochemical stabilization of soils." Die Bautechnik, No. 16, Berlin (April 1939) (translation).

7. __________, "Electro-osmosis." Proceedings, 2nd International Conference on Soil Mechanics and Foundation Engineering, vol I (1948).

8. __________, "Electrical stabilization in earthwork and foundation engineering." Proceedings, Conference on Soil Stabilization, Massachusetts Institute of Technology (1952).

9. __________, "Electro-osmotic stabilization of soils." Journal of The Boston Society of Civil Engineers, vol 39 (1952), pp 51-83.

10. __________, Review of Past and Current Work on Electro-osmotic Stabilization of Soils. Harvard Soil Mechanics Series, No. 45, December 1953.

11. Cornell University, Soil Solidification Research, vol II, Fundamental Properties, Clay-Water Systems. Final report, 1951.

12. Dawson, R. F., and McDonald, R. W., "Some effects of electric current on the consolidation characteristics of a soil." Proceedings, 2nd International Conference on Soil Mechanics and Foundation Engineering, vol V (1948).

13. Endell, K., and Hoffman, A., "Electrochemical hardening of clay soils." Proceedings, 1st International Conference on Soil Mechanics and Foundation Engineering, vol I (1936).

14. Geuze, E. C. W. A., Bruyn, C. M. A. de, and Joustra, K., "Results of laboratory investigations on the electrical treatment of soils." Proceedings, 2nd International Conference on Soil Mechanics and Foundation Engineering, vol III (1948).

15. Harvard University, Laboratory Investigations of the Effects of Electro-osmosis on Fine-Grained Soils. Report to the Bureau of Yards and Docks, Contract No. NOy-76303 (phase B), December 1953.

16. Harvard University, Laboratory Investigations of the Effects of Electro-osmosis on Fine-Grained Soils. Report to the Bureau of Yards and Docks, Contract No. NOy-76303 (phase B), January 1955.

17. ________, Laboratory Investigations of the Effects of Electro-osmosis on Fine-Grained Soils. Report to the Bureau of Yards and Docks, Contract No. NOy-76303 (phase B), January 1956.

18. Jacobs, H. S., and Mortland, M. M., "Ion movement in Wyoming bentonite during electro-osmosis." Soil-Science Society of America Proceedings, vol 23, No. 4 (1959).

19. Jumikis, A. R., "Concerning a mechanism for soil moisture translocation in the film phase upon freezing." Proceedings, Highway Research Board, vol 39 (1960), pp 619-639.

20. Karpoff, K. P., "Stabilization of fine-grained soils by electro-osmotic and electrochemical methods." Proceedings, Highway Research Board, vol 32 (1953), pp 526-540.

21. Kolbuszewski, J., "A study of the electro-chemical hardening of clay." Civil Engineering and Public Works Review, vol 47, No. 553, London (July 1952).

22. Kravath, F. F., "Soil stabilization by electro-osmosis." Military Engineer, vol 46, No. 312 (1954).

23. Lomizé, G. M., Netushil, A. V., and Rzhanitzin, B. A., "Electro-osmotic processes in clayey soils and dewatering during excavations." Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering, vol I (1957).

24. Loughney, R., "Electricity stiffens clay fivefold for electric plant excavation." Construction Methods and Equipment, vol 36, No. 8 (August 1954).

25. Maryland University, Preparation, Studies, and Performance of Investigations in Connection with the Electrical and Physicochemical Stabilization of Soils for Airfields. Contract W-49-080-eng-890, June 1951.

26. Murayama, Sakudo, and Mise, Tadashi, "On the electrochemical consolidation of soil using aluminum electrodes." Proceedings, 3rd International Conference on Soil Mechanics and Foundation Engineering, vol I (1953).

27. Oakes, D. T., and Burcik, E. J., "Electrokinetic phenomena in colloidal clays." Proceedings, 4th National Conference on Clays and Clay Minerals (1956).

28. Piaskowski, A., "Investigations on electro-osmotic flow in soils in relation to different characteristics." Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering, vol I (1957).

29. Poisson, Y., "Electrical treatment of plastic clay." Travaux, No. 164, Paris (1948). Translated by Britt for U. S. Geological Survey, January 1949.

30. Preece, E. F., "Geotechnics and geotechnical research." Proceedings, Highway Research Board, vol 27 (1947), pp 384-417.

31. Remenieras, G., Application of Electro-osmosis to the Execution of Certain Work on Water-Bearing Soils. U. S. Geological Survey Translation No. 21, 1951.

32. Richardson, H. W., "Electric curtain stabilizes wet ground for deep excavation." Construction Methods and Equipment, vol 35, No. 4.

33. Rollins, R. L., The Effect of Calcium on the Continuity of the Electroosmotic Flow Rate. Iowa State College Engineering Experiment Station, 1955.

34. __________, "The development of non-homogeneous flow condition during electro-osmosis in a saturated clay mineral." Proceedings, Highway Research Board, vol 35 (1956), pp 686-692.

35. Rzhanitzin, B. A., Electrochemical Stabilization of Clayey Ground. Moscow, 1941. Translated by V. P. Sokoloff for U. S. Geological Survey, 1946.

36. Schaad, W., "Electrical treatment of soils." 2nd International Conference on Soil Mechanics and Foundation Engineering, vol VI (1948).

37. Schaad, W., and Haefeli, R., "Electrokinetic phenomena and their use in soil mechanics." Schweizerische Bauzeitung, vol 65, Nos. 16, 17, and 18, Switzerland (1947). Translated by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

38. Shulka, K. P., "Electrochemical treatment of clays." Proceedings, 3rd International Conference on Soil Mechanics and Foundation Engineering, vol I (1953).

39. Solntzev, D. I., and Sorkov, V. S., Electrochemical Stabilization as Means of Preventing Ground Failure in Railroads. Moscow, 1941. Translated by V. P. Sokoloff for U. S. Geological Survey, 1946.

40. Spangler, M. G., and King, H. L., "Electrical hardening of clays adjacent to aluminum friction piles." Proceedings, Highway Research Board, vol 29 (1949), pp 589-599.

41. Taylor, D. W., Fundamentals of Soil Mechanics. John Wiley and Sons, Inc., New York, New York, 1948.

42. Terzaghi, K., Theoretical Soil Mechanics. John Wiley and Sons, Inc., New York, New York, 1943.

43. Terzaghi, K., and Peck, R. B., Soils Mechanics in Engineering Practice. John Wiley and Sons, Inc., New York, New York, 1948.

44. University of California (Los Angeles), Summary of Literature Survey of Electrokinetic Soil Stabilization. December 1947.

45. U. S. Army Engineer District, Washington, CE, Investigations of Methods for Increasing Subgrade Stability. Summary Report, December 1949.

46. U. S. Bureau of Reclamation, Laboratory Investigation of Electrical

Drainage and Electrochemical Stabilization of Soils. Structural Research Section Report No. SP-29, May 1951.

47. U. S. Bureau of Reclamation, Electroreclamation of Saline-Alkaline Soil, Model Tests, by H. J. Gibbs and K. P. Karpoff. Earth Laboratory Report No. EM-512, February 1958.

48. Vey, E., "The mechanics of soil consolidation by electro-osmosis." Proceedings, Highway Research Board, vol 29 (1949), pp 578-589.

49. Wang, W. S., and Vey, E., "Stresses in a saturated soil mass during electro-osmosis." Proceedings, 3rd International Conference on Soil Mechanics and Foundation Engineering, vol I (1953).

50. Winterkorn, H. F., "Fundamental similarities between electro-osmotic and thermo-osmotic phenomena." Proceedings, Highway Research Board, vol 27 (1947), pp 443-455.

51. __________, "Physico-chemical properties of soils." Proceedings, 2nd International Conference on Soil Mechanics and Foundation Engineering, vol I (1948).

52. __________, "Surface chemical properties of clay minerals and soils from theoretical and experimental developments in electroosmosis." Symposium on Exchange Phenomena in Soils, ASTM Special Publication No. 142 (1952).

53. Zaretti, L., "Notes on an application of the electro-osmotic process for the consolidation of clayey soils." L'Energia Ellectrica, vol XXVII, Italy (1950). Translated by J. V. Grasso, Harvard University.