the soil pores to the ground surface, the surficial and the undersurface flow could merge. If this should occur, the velocity of the undersurface flow would increase because of the drag (shearing stresses in this case) exerted by the upper layer of the combined stream on the lower layers. It is obvious that the "curtain" as described above should approximately follow the surface topography; this is the principal reason for the formation of subsurface-water streams over thinner ground-water layers that may completely disappear during dry seasons.

Though the term *hydrauger* as used in the Pacific Coast area may not be correct, it cannot be replaced by the term *horizontal drains*. In fact, if the pipes termed hydraugers were horizontal, water would not flow through them. The slope of a hydrauger should be greater than the gradient of the ground water; in the authors' practice a 5-percent slope is often used.

Stabilization of Fine-Grained Soils by Electro-osmotic and Electrochemical Methods

K. P. KARPOFF, *Engineer, U. S. Bureau of Reclamation, Denver*

THIS paper gives a brief explanation of the fundamental processes of stabilization by electroösmotic and electrochemical means and cites the work of early investigators. The author investigated the effectiveness of the two methods by laboratory tests on two soils. 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 evaluate and check the technique and apparatus developed. Tests included grain-size distribution, plasticity, standard compaction, triaxial shear, base-exchange capacity, X-ray diffraction, microscopy, and others. Data include time of lowering of phreatic line by well-point and by electric-potential methods, relative permeability prior to and after electroösmotic treatment. Eight figures illustrate equipment and indicate relationships established in the investigation.

● WITHIN recent years increased importance has been given to the development of practicable methods of stabilizing fine, unstable soils by removal of excess moisture or by the introduction of chemicals into the material in place. Previously, the incomplete knowledge of the physicochemical nature of earth materials was a major obstacle to this development. However, the rapid advancements made in the technology of soil mechanics and in the improvement of techniques of analyses of the mineralogic constituents, crystalline structure, and physicochemical properties of earth materials have opened new fields for soil mechanics engineers.

Two important techniques developed to stabilize fine-grained soils are the electroösmotic and electrochemical processes. These processes produce a movement of liquid through porous material under the influence of an electromotive force. The movement of liquid through porous material was described the first time in 1808 by Reuss (5, 7, 8, 9, 10). This movement of liquid results from electrophoresis in electroösmotic phenomenon. Electrophoresis is the transfer of particles in suspension due to the action of the electrical field, created by the flow of the current, on electrical charges carried by the particles.

Electrophoresis and electroösmosis are interpreted from the hypothesis of the "double layer," formulated for the first time in 1861 by Quineke. This hypothesis depends upon the supposition that a spontaneous electrification exists at the contact surface of a solid and a liquid prior to any external electrical action. The surface of the soil is usually charged with a certain electrical layer, and an

electrical layer of opposite sign appears in the liquid. The solid-liquid contact surface (interface) acts somewhat as a dielectric of a classical condenser. In the case of wet soil, the water phase will be charged positively and the soil particles charged negatively. When an electric field is applied to the wet soil, water tends to move in the opposite direction to the soil, but in general, due to the usual immobility of soil particles, only the water moves.

Recent physical and physicochemical wet-soil investigations have shown that during electrical treatment positive ions (cations) attached to the clay particles are released into solution, and they, together with cations derived from water soluble salts in the soil, migrate toward the cathode. The naturally occurring metallic cations are in part replaced by H^+, and the characteristics of the clay are changed (1, 9, 11).

Electroösmotic flow through a soil depends upon two general factors: (1) the properties of the soil and liquid, i.e., porosity, electrical resistance of the solid and the liquid, viscosity, and dielectric constant; and (2) the properties of the electrodes, i.e., the composition, conductivity, dimensions, and spacing (4).

In engineering practice, electroösmotic or electrochemical stabilization is applied to such souls as clay, sandy clay, loess, sandy silt, and silt. It has been used to overcome difficulties in excavation and soil stabilization when the high retention forces (electrostatic forces) of the water film surrounding soil particles and low permeability of the soil render the usual mechanical or hydraulic methods ineffective (5, 21).

First investigated in Germany in the mid-1930's, the electroösmotic methods have been used successfully in a number of applications. In brief, the electroösmotic stabilization of fine-grained soil is made by the passage of direct current through the soil between embedded electrodes. The current causes the water in the soil to move from the positive electrode and toward the negative electrode. If a well-point is used as the negative electrode, the water which collects at the electrode can be pumped out, thus effecting drainage of the soil and resultant stabilization. The electroösmotic method produces a temporary stabilization of the soil, although some permanent change in exchangeable cations is

effected; and with prolonged treatment, less stable clay minerals might be partially decomposed (Table 2, Column 4; Fig. 1).

The electrochemical method produces a permanent stabilization of the soil. This has been accomplished in the laboratory by the use of two embedded electrodes of like metallic substance. These electrodes may be iron, copper, aluminum, brass, or gold-plated brass. Stabilization is accomplished by ap-

TABLE 1

TEST RESULTS OF THE ELECTROÖSMOTIC FLOW AGAINST HYDRAULIC GRADIENT $i = 4$, GRAND COULEE SOIL

Voltage	Effective hydraulic head in feet	Theoretical flow[a] at 20 C. $\times 10^{-4}$ ml./min.	Observed flow[b] at 20 C. $\times$ 10^{-4} ml./min.
0	1	8.9	8.9
0.5	0.50	4.4	1.4
1.0	0.02	0.2	−1.9
1.5	−0.30	−2.7	−8.0
2.0	−0.80	−8.0	−11.4
3.0	−1.80	−19.8	−20.8
5.0	−3.60	−40.4	−30.8

[a] The theoretical flow was computed from the formula $Q = K_1(1 - h)\dfrac{A}{L}$; where K_1, the coefficient of permeability in feet per year varied with respect to the voltage (V) according to the equation $K_1 = 0.178 + 0.03 V$; h was the hydraulic head in feet developed by the applied voltage; L the length of the flow path; and A the cross-sectional area.
[b] Observed flow determinations for each voltage were made under similar laboratory conditions. The observation of each flow was made for a period of 7 hours.
Note: Several attempts were made to obtain observations over a wide range of electromotive force during electroösmotic flow tests, in order to determine a desired electric potential for treatment of the undisturbed sample. Due to the large hydraulic gradient developed (Fig. 6c) and to limited facilities, the highest potential for which flow could be measured was 5 volts. The measurements of flow produced by electromotive forces from 0 to 5 volts were conducted on a cylindrical soil specimen in such a manner that the electric current was acting in opposition to a 1-ft. hydraulic head.
A negative sign (−) indicates a reversed flow of water (extraction).
Remarks: It can be seen that the observed reverse flow has a higher negative magnitude than the computed flow; it appears from these data that the discrepancy between the observed flow and the theoretical flow would be expected to increase at higher voltage.
On the basis of 33 pilot experimental tests which were performed on this type of soil and previous experience, it was assumed that electromotive force between 30 and 40 volts would be satisfactory for electrical treatment of the soil without fear that the clay materials would be decomposed or that the soil would be overheated.

plication of a direct current into the wet, unstable material through the embedded electrodes and by a simultaneous introduction of the desired concentration of a chemical solution, or mixture of solutions (Table 2a), through a hollow, perforated positive electrode which causes cation exchange in the soil. However, if the soil responds to stabilization by aluminum cations, the process can be simplified by embedding aluminum electrodes

TABLE 2
SUMMARY OF THE LABORATORY TEST RESULTS
Effect of Electroösmotic and Electrochemical Treatment on the Physical Properties of Granby Pump Canal Soil

Physical and chemical properties of soil	Field condition (average of three samples)	Method of treatment of soil		
		Well-points (vacuum 10 inches of Hg)	Electroösmotic (emf 35 v and vacuum 10 inches of Hg)	Electrochemical (emf 35 v vacuum 10 inches of Hg and 4.3 ml. of 2-percent $CaCl_2$ 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, minutes	Immediately	8.5	11.75	4,320+
Voids ratio	0.74	0.63	0.59	0.60
Permeability ft. per yr. at 20 C.	14.73	—	9.91	
Exchange capacity, me. per 100 grams	12.38	12.38	At anode 11.25 At cathode 11.75	At anode 8.75 At cathode 9.26
Energy requirement for sample, watt-hour	—	—	0.63	1.18
Dewatering rate of sample, ml. per min.	—	—	0.46[a]	0.62[b]

Remarks: Duration of each treatment was 30 min.
[a] Equivalent 0.26 gal. per min. per cu. yd.
[b] Equivalent 0.50 gal. per min. per cu. yd.
Electrochemical treatment requires about 5.0 gallons of 2 percent $CaCl_2$ solution per cubic yard of soil.
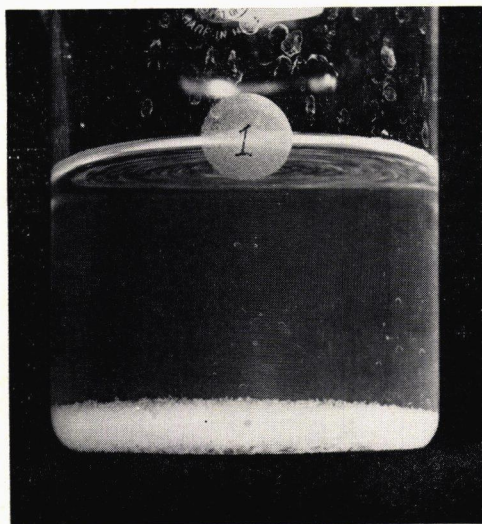Equivalent energy requirement about 3 to 5 kwh. per cu. yd.

Figure 1. A precipitate of aluminum hydroxide, formed in the cathode compartment of the electrodialysis test apparatus after the second period of 76-hour application of the electric potential (100 volts). This precipitation indicates decomposition of clay minerals.

in the soil and employing an electromotive force without the use of chemicals. Electrochemical stabilization takes place through progressive dewatering and stabilization of the soil as the interstitial aqueous solution is driven toward the cathode by the impressed potential difference between the electrodes. The aluminum or the hollow, perforated, metallic anode releases cations which migrate through the soil toward the cathode and progressively displace the original cations in the clay constituents of the soil. By this process a more stable soil is produced from the original saturated unstable material, resulting in a decrease in void ratio and absorption, change in permeability, an increase in shear resistance of the soil, and resistance to softening in water (Figs. 7 and 8).

Since each soil may react differently, preliminary information on the possibilities of electroösmotic or electrochemical stabilization should be obtained from laboratory tests. In these tests the samples should duplicate the particular field conditions as nearly as possible.[1]

[1] The following field investigations will be necessary: (1) determine the elevation of the water table in the field and direction of ground-water flow; (2) make a qualitative analysis of the soil water to identify any electrolytes which might produce unstable or undesirable conditions in the soil; (3) determine the field density and moisture content of the soil; and (4) obtain representative undisturbed samples.

PRELIMINARY LABORATORY INVESTIGATIONS AND ANALYSES

Apparatus and techniques have been developed in the Engineering Laboratories of the Bureau of Reclamation in Denver primarily to study the practicability of improving soil properties by these methods. Photographs of the apparatus and accompanying

tention capacity. The tests on the original material indicated the following properties:

Specific gravity (using the nonpolar liquid-xylol).. 2.634
Percent retained on No. 4 screen............ 1.5
Percent (No. 4 to 0.05 mm.)................. 51.6
Percent (0.05 to 0.005 mm.)................. 45.6
Percent (less than 0.005 mm.).............. 1.3
Liquid limit............................... 22.4
Plastic limit.............................. N.P.
Standard compaction maximum density..... 118.9 pcf.
Optimum moisture.......................... 13.7%

TABLE 2a
SUMMARY OF THE LABORATORY TEST RESULTS
Effect of Electrochemical Treatment on the Physical Properties of Grand Coulee Dam Soil (Undisturbed Sample)

Specimen No.	Specific gravity	Dry density	Moisture content	Extracted water in percent of dry weight	Deviator stress	Tan ϕ	Rate of percolation ft. per yr. at 20 C.	Increase of strength	Remarks
		pcf.			*psi.*			*%*	
Untreated Soil[a]									
1	2.756	86.0	34.9		38.9	—			Rate of permeability after electroösmotic treatment was = 0.483 ft. per yr. at 20 C.
3	2.756	87.2	33.4		38.0	—			
4	2.756	87.1	33.8		33.5	—			
Average	2.756	86.9	34.0						
1a[b]	2.756	88.1	32.0						
1a[c]	2.756	85.9	36.4			0.049			
Electrochemically Treated Soil									
1ae	2.756	88.1	33.3	3.1		—			Used aluminum electrodes. Solution added: Equal parts of 5% AlCl₃ and 2-½% CaCl₂, immersed in 3% aliphatic carboxyl (AM 1180) solution (water repellent agent)
5	2.756	87.4	33.6		49.7	0.200		28	
6	2.756	87.4	33.6		45.5	0.268		20	
7	2.756	88.1	33.5		53.2	0.139		59	
Average	2.756	87.6	33.6					36	

[a] Atterberg limits: L.L. = 60.0 percent P.I. = 33.0 percent
[b] Before percolation test
[c] After percolation test (19 days)
Note: The average strength of soil was significantly increased by electrochemical stabilization in spite that the density and moisture content of untreated and electrochemically treated soil practically were the same. This phenomenon shows clearly that the changes in physicochemical properties of the soil are responsible for the improved strength of the material. The electric energy requirement for stabilization of the laboratory specimen was 12.1 watt-hours, equivalent to about 10 kwh. per cu. yd. of soil.

laboratory test results are presented here for two types of soil. The first type of soil was thoroughly investigated in the laboratory to develop a technique and apparatus to be used. The second type of soil was investigated to evaluate and check the technique and apparatus developed.

The first type of soil was obtained from the Granby Pump Canal of the Bureau of Reclamation Colorado-Big Thompson Project in Colorado (11). This soil was, in general, of a glacial lacustrine origin consisting of rock flour, silt, sand, gravel, and occasional boulders. It was classified as a fine sandy silt, was non-cohesive, and had a high water-re-

Triaxial shear test at standard compaction conditions indicates:

(1) Cohesion............................... 4.00 psi.
(2) Tangent ϕ............................ 0.71

Other data relative to the physical properties of the soil are given in Table 3.

It was apparent that the soil must undergo some changes in physicochemical properties for adequate stabilization. For this reason, a study was made of the petrographic and base exchange characteristics as a means of evaluating the changes which take place upon the passage of a current through the soil mass.

The electrodialysis tests on the original material indicated the following results:

Total base exchange capacity of
the soil.................... 12.38 me. per 100 g.
Exchange capacity in the soil
sample:
Potassium.................. 2.04 me. per 100 g.
Sodium.................... 0.55 me. per 100 g.
Calcium.................. 17.48 me. per 100 g.
Magnesium................ None
Iron...................... None
Aluminum................. None

The study of X-ray diffraction patterns shown in Figure 2 also shows this same general trend. Pattern A made from the original sample indicates the following approximate composition:

Quartz........................... 30 to 35 percent
Feldspar......................... 35 to 40 percent
Biotite.......................... 5 percent
Montmorillonite.................. 5 to 8 percent

TABLE 3
PHYSICAL PROPERTIES OF SOIL FROM GRANBY PUMP CANAL

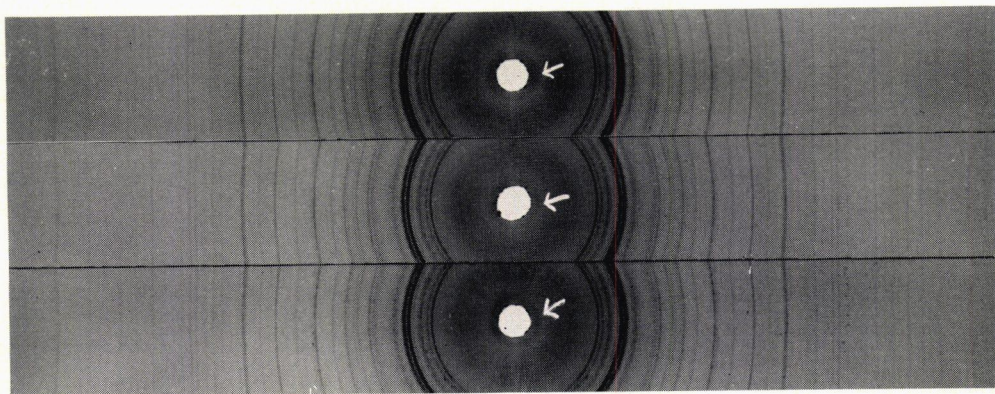| Sample	Wet density	Moisture content	Dry density	Void ratio	Porosity	Penetration resistance	Percola-tion	Remarks
	pcf.	%	pcf.		%	psi.		
1	123.21	26.1	97.71	0.68	40.5	4.00	14.78	At the toe of slope
2	122.86	26.1	97.43	.69	40.8	—	—	At the toe of slope 10 in. below an excavated surface
3	118.00	33.1	88.66	.85	45.9	—	—	From the bottom of canal at center-line
Std. compaction	118.93	13.7	104.6	.57	36.3	680.0	12.85	

Figure 2. X-ray diffraction patterns of Granby Pump Canal material containing montmorillonite-type clay. Concentration of the montmorillonite-type clay on the patterns is indicated by the intensity of the innermost line (arrow): Top, before electroösmotic treatment; center, at cathode after electroösmotic treatment; bottom, at anode after electroösmotic treatment (intensity of the line is more pronounced than in upper patterns.)

Also, the electrodialysis results indicated that the introduction of high electric potential (in order of 100 volts) during electroösmotic treatment of the soil would decompose the clay mineral. This gives an indication that high voltage may be undesirable. Precipitation of aluminum hydroxide formed in the cathode compartment of the electrodialysis apparatus (11) as a result of the decomposition of the clay mineral (Fig. 1).

The microscopic analysis of soil indicates the presence of small amounts of volcanic glass, hornblende, zircon, hematite, apatite, magnetite, and rutile, in addition to the constituents already identified by X-ray diffraction (11).

The second type of soil was an undisturbed sample obtained from the area of the right switchyard of Grand Coulee Dam of the Bureau of Reclamation Columbia Basin

Project in Washington. This soil was of a glacial lake deposit and was identified as a varved clay of the Nespelem formation. It was classified as a medium fat clay.

A summary of the physical properties of the undisturbed sample is given below:

Specific gravity (using the nonpolar liquid-xylol)........................ 2.756
Dry density (average of three specimens)........................ 86.9 pcf.
Moisture content (average of three specimens)................... 34.0
Compressive strength (average of three specimens)................ 36.8 psi.
Tan φ (could not be determined because of varved structure of clay)..
Rate of percolation (at 20 C.)......... 0.049 ft. per yr.
Atterberg limits: L.L. = 60.0 percent, P.I. = 33.0 percent

The petrographic examination of the original material indicated the following:

1. The soil in a moist condition is dark gray, soft, and very fine-grained and becomes plastic when wet. When dry, the soil is light gray. Dry lumps of the soil macerate rapidly to a mud after immersion in water. If the soil is wetted slightly with water, it becomes very slick to the touch.

2. Under the microscope the soil is seen to be composed of very fine-grained quartz, plagioclase, orthoclase, and microcline, with very small amounts of biotite, muscovite, chlorite, and hornblende (mostly in silt sizes) intermixed with a large amount of clay and claylike minerals. Zircon and apatite occur in very small amounts. Calcium montmorillonite is present in small to moderate amounts. However, the principal clay constituent is an illite-vermiculite type. The X-ray diffraction pattern of this complex clay mineral indicates that the clay is very similar to illite; but upon calcination the structure decomposes to forsterite, which is a typical thermal decomposition product of the vermiculites. Illite-type minerals decompose mainly to spinel. The eight principal mineral constituents of the sample are listed below with their amounts estimated in percentage:

Mineral	Estimated percentage
Illite-vermiculite...........................	44
Montmorillonite............................	15
Quartz....................................	10
Feldspars.................................	10
Jefferisite................................	5
Mica.....................................	5
Chlorite..................................	1
Calcite, hornblende, zircon, and apatite........	3
Total..................................	93

3. The granular components of the soil are mostly smaller than 0.009 millimeter with small percentages of grains as large as 0.10 millimeter in diameter.

The properties of the soil as determined by chemical analysis were as follows:

pH of saturated paste.. 8.1
Extracted potassium ... 0.80 me. per 100 g. of soil
Water-soluble potassium................... 0.02 me. per 100 g. of soil
Exchangeable potassium (K+) .. .. 0.78 me. per 100 g. of soil
Extracted sodium....... 1.25 me. per 100 g. of soil
Water-soluble sodium... 0.34 me. per 100 g. of soil
Exchangeable sodium (Na+)............... 0.91 me. per 100 g. of soil
Total exchange capacity of soil 25.9 me. per 100 g. of soil

Exchangeable calcium (Ca^{++}) was not determined because of the presence of carbonates in the soil.

It is seen from all the preliminary laboratory investigations that the second type of material represents a complex clay mineral soil which is slightly alkaline with a total base-exchange capacity of 25.9 me. per 100 g., sodium being the predominant cation.

These preliminary laboratory investigations and analyses of the soils suggested another approach to the study of soil stabilization, i.e., the electrochemical method, consisting of replacement of undesirable cations by desirable electrolytes.

DESCRIPTION OF APPARATUS AND TECHNIQUE

The apparatus in Figure 3 was used for the investigation of the change in the position of the phreatic line with time, using different methods for dewatering the Granby Pump Canal material. The test cell consisted of two compartments separated by a partially perforated partition. A soil prism was placed in the larger compartment which was fitted with three piezometers. The smaller compartment of the cell represents a constant head reservoir for exerting a desired hydraulic head to the soil prism. The test results obtained are given in Table 4 and are expressed graphically in Figure 4.

The test using the apparatus in Figure 3 was performed using water 5 in. deep in the reservoir and without suction of water from the well-points. On the wall of the plastic box are shown the positions of the phreatic line at intervals of 5 min. The list of the equipment which was used during the test as numbered in the photograph includes: (1) aspirator, (2) manometer, (3) water trap, (4) plastic test cell containing soil and 5-in.-deep

water in the reservoir, (5) cathode electrodes (well-points), (6) anode electrodes (copper strips), (7) thermometer, (8) piezometer, (9) scale (200-lb. capacity), (10) ammeter, (100 ma.), (11) voltmeter (300 v.), (12) rectifier

the well-points can be left on until a stable condition is reached, at which time an automatic float or other device would shut off the power (d.c.). As soon as the water level in the well-point rises to a predetermined acceptable
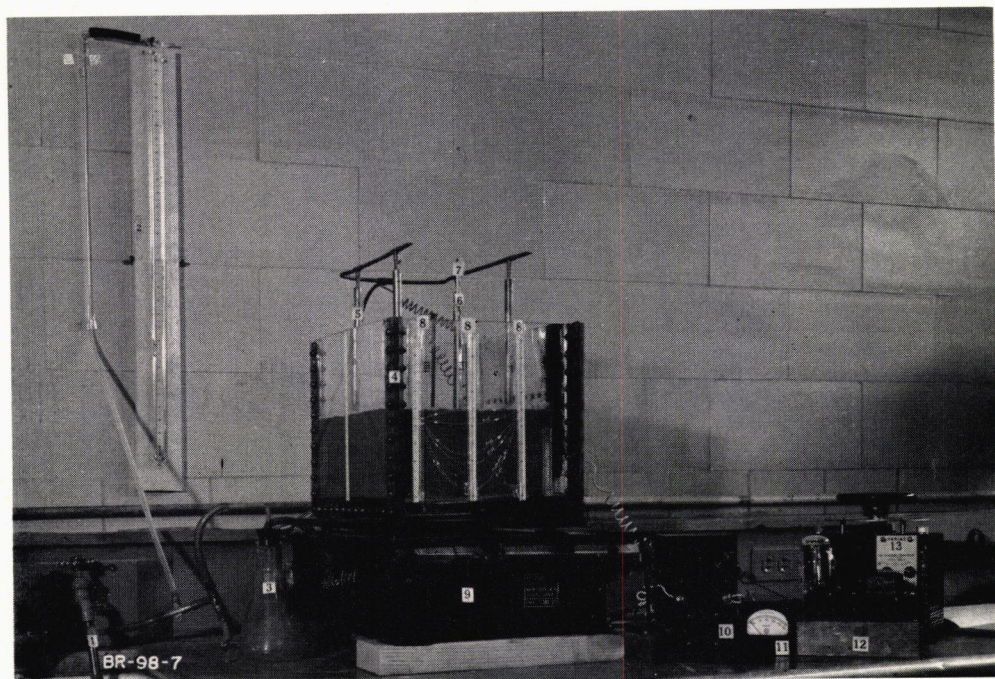

Figure 3. Apparatus for determining effect of electric potential on position of phreatic line.

TABLE 4

Method of treatment	Observed time for lowering of the phreatic line	Time of recovery of the phreatic line (7 inches of hydraulic head)
	min.	*hr.*
Well-point (vacuum 2 inches of mercury)	47.5	—
Electric potential (35 volts)	20.0	178.0
Electric potential (35 volts) in conjunction with well-points (vacuum 2 inches of mercury)	20.0	66.0

(150 v. and 300 ma. maximum output), and (13) variable transformer, Type 100-Q.

This apparatus and test results (see Fig. 4) indicate that a saving in power can be achieved in actual practice by intermittent operation. Electric power used for pumping water from

maximum, the automatic device would turn the electric power on and re-establish the direct current through the soil.

From Figure 4 it is seen that recovery of the phreatic line is a very slow process, thus intermittent operation can result in appreciable savings in the cost of electroösmotic stabilizing of saturated, fine-grained soils.

Figure 5 is a photograph of the apparatus used in the laboratory to determine (1) the coefficient of permeability of the soil prior to and after electroösmotic treatment, (2) the relationship between voltage and hydraulic head, (3) the electroösmotic flow against a designated hydraulic head or gradient, and (4) the coefficient of "osmotic" permeability (K_e cm. per sec. per volt per cm.) for determination of the approximate theoretical flow of water produced by different electromotive
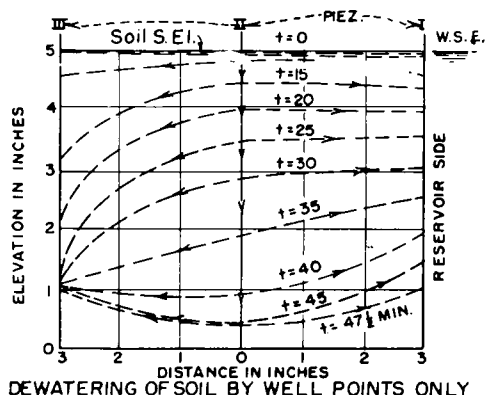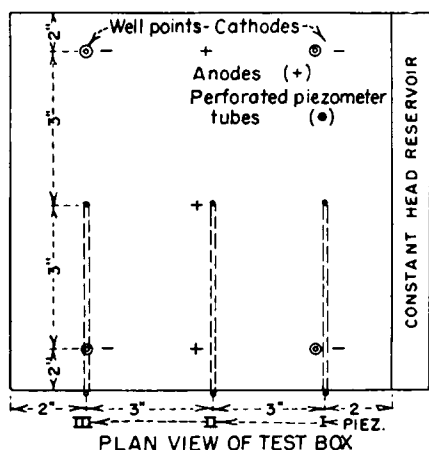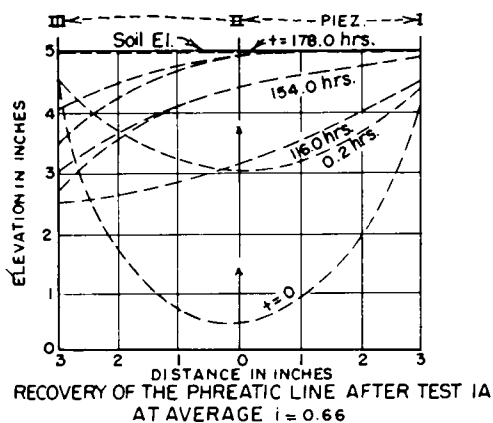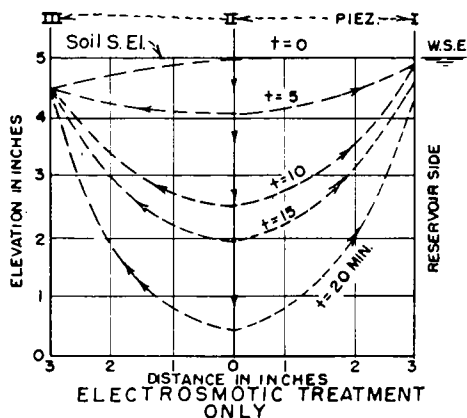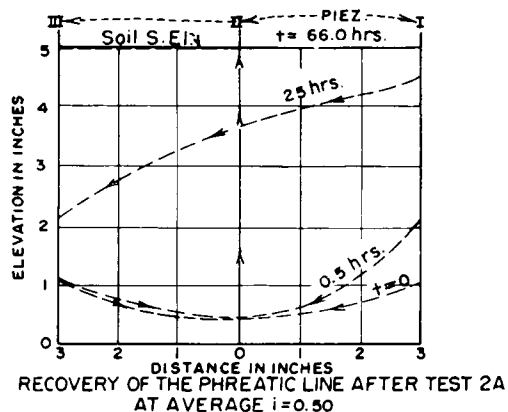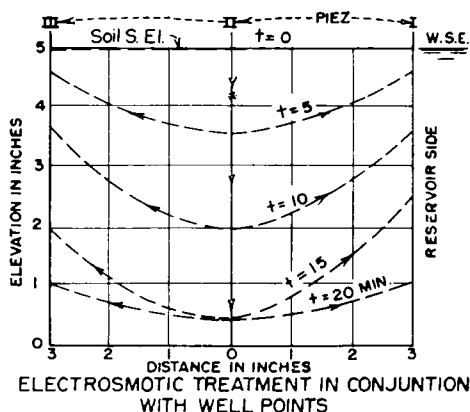
Figure 4. Effect of electric potential on position of phreatic line.

force. This apparatus was assembled in such a manner that all the above tests could be run in succession without disturbing the soil sample.

The hydraulic requirement for each test was obtained simply by the manipulation of valves. The percolation test prior to and after electrical treatment of the soil was conducted by subjecting the soil sample to a designated hydraulic head through the water system (7),
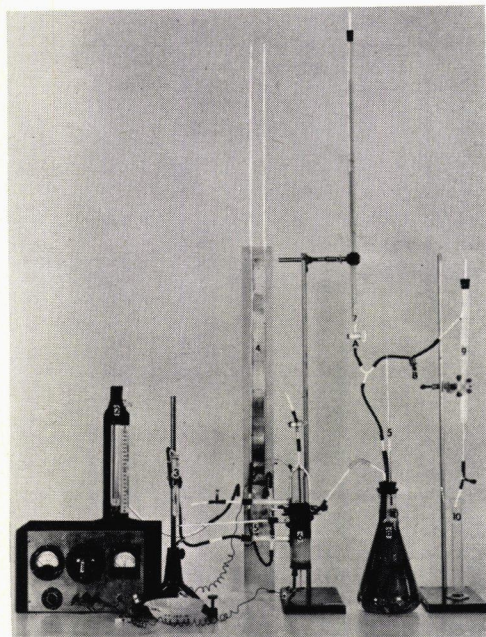

Figure 5. Equipment (see text) includes: (1) direct-current power supply, (2) mercury manometer, (3) overflow tank, (4) piezometer tubes, (5) thermometers, (6) glass cell containing specimen and gold-plated electrodes, (7) constant-head tank, (8) deaired-water supply tank with rubber balloon diaphragm, (9) overflow constant-head tank, and (10) graduated cylinder.

(8), (6), (4), and (3) with Valve A open and Valve B closed.

The test for determining the relationship between voltage and hydraulic head required closing the water supply system (7); establishing equilibrium in the piezometer tubes (4); applying the electropotential (1); and keeping the water elevation in the overflow tank (3) constant. The observation of the hydraulic head was obtained by means of a piezometer (4) or by a mercury manometer (2).

The test for determining an electroösmotic

flow against a designated hydraulic head consisted of the following procedure: Introduction of the hydraulic head by means of constant head tanks (7) and (9) and application of the electromotive force opposing the hydraulic head. The positive flow was observed in tank (7) (Valve A open and Valve B closed), and by closing Valve A and keeping Valve B open, the negative flow was accumulated in tank (9) and was measured by means of the graduated cylinder (10).

The test for determining a coefficient of osmotic permeability[2] (K_e) for different electromotive forces consisted of: (1) establishing zero gradient in piezometers and overflow tanks (3) and (9) by means of the constant head tank (7) (Valves A and B open); (2) application at a certain time of a designated electromotive force through a specimen and accumulation of the flow water in tank (9); (3) measurement of the accumulated water (Q_e) in tank (9) by means of a graduated cylinder (10); and (4) computation of the coefficient of osmotic permeability by using the following equations:

$$K_e = q_e \frac{L}{V} \text{ cm. per sec. per volt. per cm.}$$

where:

$q_e = \dfrac{Q_e}{tA}$ is unit flow per unit time per unit area of specimen

L = length of specimen in centimeters

V = electromotive force in volts

t = observed time in seconds

A = cross-sectional area of specimen in square centimeters

A relief valve provided a means of discharging gas which accumulated at the top of the apparatus during the passage of electric current through the soil. The gas was released frequently.

The permeability results obtained by using the apparatus were as follows:

	Granby Pump Canal soil	Grand Coulee Dam soil
Coefficient of permeability of the soil prior to the electroosmotic treatment (disturbed at P.L.)	14.780 ft./yr.	0.178 ft./yr.
Coefficient of permeability of the soil after electroösmotic treatment	9.910 ft./yr.	.483 ft./yr.

[2] The technique for determining K_e has been developed recently and was not applied during the tests described in this paper.

Other results are indicated in Figures 6a, 6b, 6c, and Table 1.

After completion of the above tests an electromotive force of 35 and 30 volts was selected for electrochemical stabilization of
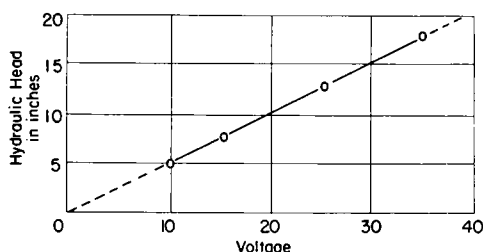

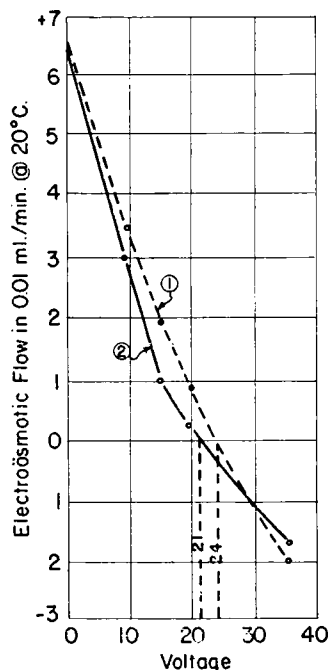Figure 6a. Relationship between voltage and hydraulic head, Granby Pump Canal soil.

Figure 6b. Electroösmotic flow against 12-in. hydraulic head: Curve 1, computed values of flow on assumption that coefficient of permeability varies on a straight line between limits of 14.73 and 9.91 ft. per yr.; Curve 2, observed values of flow at various voltages. For Granby Pump Canal soil.

Granby Pump Canal and Grand Coulee Dam soil, respectively (Fig. 6 and Table 1). The apparatus illustrated in Figure 5 was modified for the electrochemical treatment by adding a chemical supply system. During stabiliza-

tion of the sample the desired chemical solution was applied at the anode (+) and a vacuum was applied at the cathode (−)[3] simultaneously with the application of the electric potential. The soil samples after treatment were removed from the glass cylinder,[4] and the physical and physicochemical properties of the stabilized soil were measured to compare with those obtained before treatment.

Tables 2 and 2a summarize results obtained from the data of laboratory tests on the effect of electroösmotic and electrochemical treatment of the soil samples. The following changes were apparently effected: (1) decrease in moisture content, (2) increase in density, (3) increase in cohesion, (4) increase in internal friction, (5) increase in penetration resistance, (6) change in the base-exchange capacity, (7) change in permeability, and (8) increased resistance to maceration in water.

CONCLUSION

The main object of these research studies was to develop the apparatus and methods of procedure for the measurement of changes induced in a soil by various methods of electrical and electrochemical treatments and to become acquainted with the various problems involved in these types of stabilization. In addition, it was desired to show that the physicochemical properties and mineralogy of the soil are important factors in electroösmotic or electrochemical stabilization. It is felt that the objectives of the program have been adequately achieved in that equipment and techniques have been developed which will aid in the analysis of future problems, and that many of the problems encountered in electrical treatment of soils have been studied sufficiently to permit such definite recommendations.

It is evident from this study that laboratory tests and field correlation are required prior to application of the electroösmotic or electrochemical stabilization to any given problem in the field.

The limited data and laboratory test results presented in this paper should not be considered as conclusive for all soils, but rather as indicative of the possible value of these

[3] The Grand Coulee soil was stabilized without application of a vacuum at the cathode (−).
[4] The glass cylinder was replaced by a plastic cylinder (4 by 4 in.) for later tests because it was easier to handle.
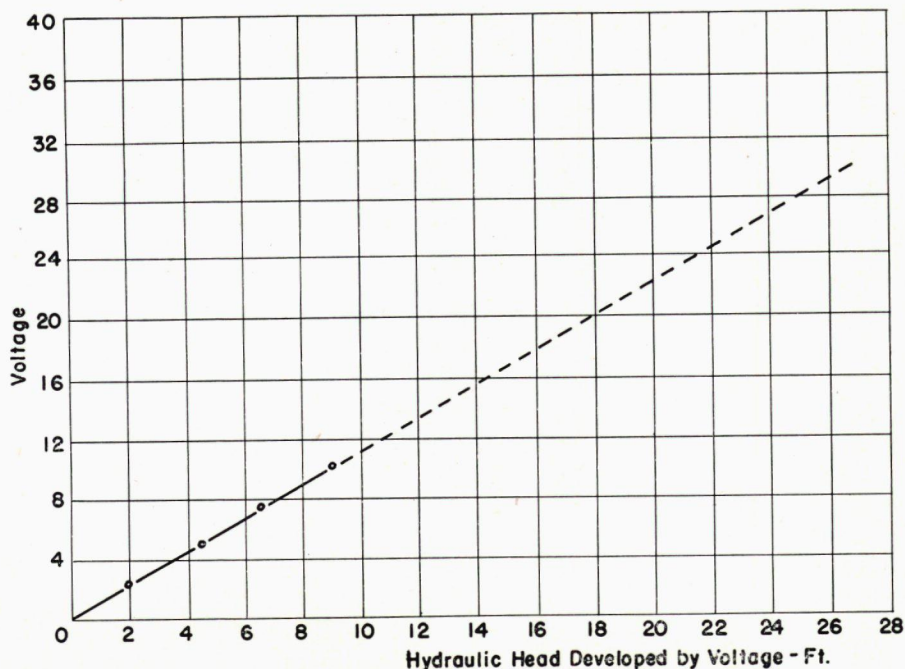
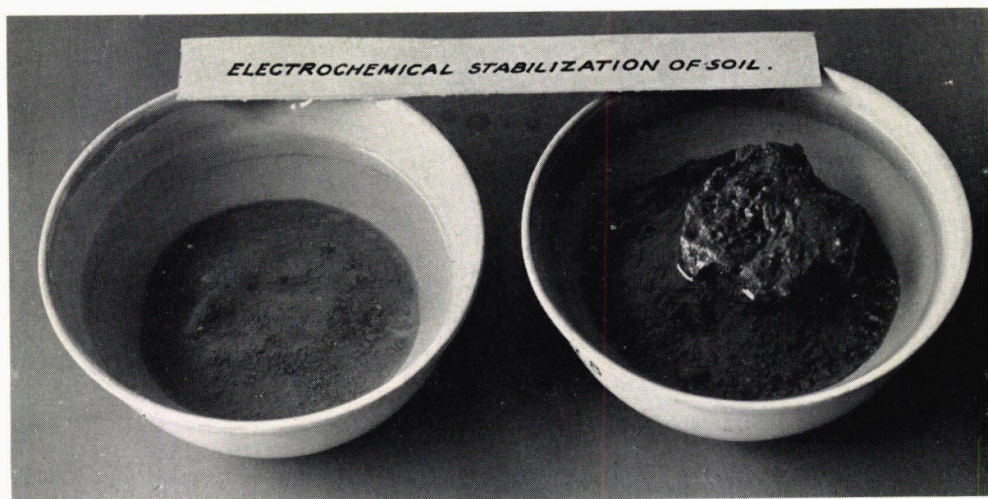Figure 6c. Relationship between voltage and hydraulic head, Grand Coulee soil.

Figure 7. Slaking of the stabilized soil, Granby Pump Canal: Left, specimen treated with 2-percent Na_2SiO_3 solution shows no stability in water, disintegrating after 10 min.; right, specimen treated with 2-percent $CaCl_2$ solution shows improved stability, disintegrating only partly after being submerged 72 hr.

methods for stabilization. On the basis of these limited tests, the tentative conclusion may be made that the electrochemical method of treatment of the soil permits not only a reduction in the moisture content, tending toward a stabilizing action, but at the same
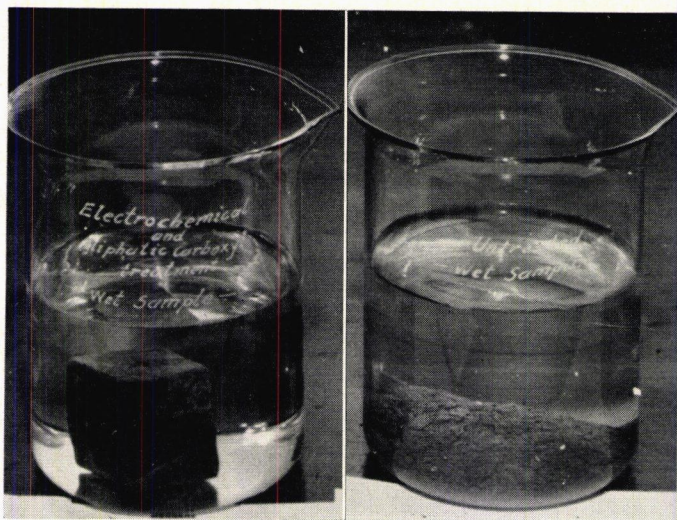
Figure 8. General view of the slaking test on Grand Coulee soil: Left, treated with 5-percent AlCl₃ + 2-½-percent CaCl₂ and 3-percent aliphatic carboxyl solution, shows perfect stability, firm and strong after being submerged for 94 hours; right, undisturbed, untreated sample (at 32.8 percent of natural moisture) shows no stability in water, having disintegrated after 10 min. forming conical pile of mud with suspension of colloids in water.

time brings about definite changes in the physicochemical properties of the material and possible changes in the structure of the clay particles. The tests further indicate that the electrochemical method in most instances makes possible a greater improvement in the physical properties of a soil than the electro-osmotic treatment alone.

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DISCUSSION

R. TORRENCE MARTIN, *Massachusetts Institute of Technology*—The author has taken a great deal of data in order to follow changes that take place in the soil on treatment, and he is to be highly commended for his thoroughness. One of the major points of the paper is that electroösmotic stabilization of soil causes considerable destruction and migration of clay minerals. The destruction of clay minerals by the passage of an electric current has been shown by many investigators.

It is not the purpose of this discussion to detract from the wealth of information in this paper, but to attempt clarification of what actually occurred. Three experimentally observed phenomena used by the author for making the point that clay minerals are destroyed during treatment are: (1) the precipitation of aluminum hydroxide in the cathode compartment during electrodialysis; (2) the change in intensity of the (001) montmorillonite spacing as a result of treatment; and (3) the decrease in exchange capacity as a result of treatment.

The formation of aluminum hydroxide precipitate in the cathode compartment during electrodialysis in itself is not very conclusive as evidence for decomposition of clay minerals, because many feldspars and micas are less stable than the clay minerals and contain more aluminum. This, coupled with the fact that the percentage of clay is low compared to the amount of feldspar and mica, would seem to indicate that the non-clay minerals provided most of the aluminum for the aluminum hydroxide precipitate formed.

Figure 2 presents X-ray powder patterns on soil from Granby Pump Canal before and after treatment. The weak (001) montmorillonite spacing on the original soil as shown in Pattern A has disappeared in Pattern B, which was taken after treatment on soil from the region of the cathode. Material from the region of the anode (Pattern C) gave a stronger (001) montmorillonite spacing than the original soil. The interpretation of these data is that the treatment decomposed the clay and caused its migration to the anode. Questions of experimental procedure arise. The increased intensity of Pattern C could be simply due to particle orientation. There is also a question as to whether these patterns are the only ones on which interpretation is based, or whether the patterns presented are merely representative of those studied, because the variability between Patterns A and C is within expected limits in

X-ray patterns of montmorillonite unless extreme care is used in sample preparation. Pattern B could lack orientation, thus decreasing the intensity of the basal reflection, and the absence of a (001) spacing does not necessarily mean migration or decomposition of the clay. It might be more significant if rather than destroying the clay, electricity simply reoriented the particles; therefore, this observation by the author is extremely interesting and would bear further study.

The decrease in exchange capacity given in Table 2 is presented as evidence for the destruction of clay minerals. From the composition and grain-size data, it is noted that the Granby Pump Canal soil contains quartz, feldspar, and mica in the fraction greater than 5 microns, and montmorillonite in the fine portion. While minerals such as mica, feldspar, and quartz may have an exchange capacity if ground fine enough, certainly the coarse material of this sample contributes little to the exchange capacity of the soil; therefore, the only mineral contributing to exchange capacity is montmorillonite. Allowing 100 me. per 100 gm. as exchange capacity for montmorillonite, and the maximum amount in the sample of 8 percent, one can account for two thirds of the exchange capacity of the soil. This immediately suggests the presence of organic matter. With exchange capacity as high as 400 me. per 100 gm., very little organic matter is required to make up a sizeable fraction of the total exchange capacity. Recent work by J. E. Dawson at Cornell has shown that soil organic matter is easily broken down on electrodialysis, and in fact, that organic matter has considerable water solubility. In view of this, it seems quite likely that the decrease in exchange capacity is due to the removal of organic matter, and that this removal is more effective when calcium chloride is added because the electrolyte increases the charge density and the solubility of organic matter. It would be interesting to compare the amount of organic matter in the two soils with the decrease in exchange capacity.

These comments are not meant to disprove the conclusions reached by the author but rather as supplementary interpretive information.

K. P. KARPOFF, *Closure*—The author appreciates the discussor's interest and contribution to this new and relatively unexplored approach to the solution of a long-existent problem. The author will attempt to clarify the points brought out by Martin.

The precipitation of $Al(OH)_3$ (Fig. 1) in the cathode compartment of the electrodialysis apparatus, after application of an electric potential of 100 volts for 152 hr., can be explained as decomposition of clay minerals on the basis of the following:

1. The particle size of the clay is much smaller than that of the feldspar or biotite; therefore, the clay particles should be more susceptible to the destructive force of the 100-volt potential than the feldspar or biotite particles.

2. The percentage of aluminum in feldspar is usually in the range from 18.4 to 36.7 percent as Al_2O_3; however, in montmorillonite, alumina ranges from 5.0 to 31.0 percent. Biotite usually contains 13.7 to 18.6 percent of aluminum as Al_2O_3.

3. If feldspar and biotite are less stable than clay, then why should the precipitation of $Al(OH)_3$ in the cathode compartment appear only in the last few hours of the 152-hour treatment and not before? The precipitation occurred only when the exchangeable cations of the soil as Na^+, K^+, and Ca^{++} were practically extracted or replaced by hydrogen ion.

4. The discussion concerning the higher stability of montmorillonite clay in comparison to feldspar and biotite is questionable. However, it would be desirable to check this experimentally, subjecting pure montmorillonite clay, feldspar, and biotite separately to an electromotive force of 100 volts in the electrodialysis apparatus.

Considering the above statements, the author feels that during the electroösmotic stabilization of this particular soil, the high electric potential may have produced the following undesirable results: (1) decomposition of clay minerals; (2) formation of a dry crust at the anode which substantially increases the resistance of the circuit; and (3) loss of energy due to heating of the soil.

Concerning the change in intensity of the montmorillonite concentration as a result of the electroösmotic treatment at 35.0-volt potential for a period of $\frac{1}{2}$ hr., the author feels the following explanations are valid. A

diminution of the coefficient of permeability of soil after electroösmotic treatment (from 14.78 to 9.91 ft. per yr.) led to the X-ray diffraction studies because, according to other investigators, the soil after electrical treatment usually becomes more pervious:

1. The X-ray diffraction patterns (Fig. 2) for the Granby Pump Canal soil show the existence of the electrophoresis phenomenon in spite of the fact that the tested material was not in a suspended condition. It is believed that, due to the poor gradation of the soil, the colloidal particles of the montmorillonite clay migrated through the void channels of the soil skeleton toward the anode, forming a more impervious media in the vicinity of the anode.

Therefore, the interpretation of this phenomenon is that the treatment of the Granby Pump Canal soil, by 35 volts for ½ hr., causes the migration of the clay particles to the anode (+) without any sign of destruction of the particles.

2. Pattern B does not express orientation of the montmorillonite clay particles because the preparation of the samples for X-ray study is such that the specimen does not represent the undisturbed condition of the treated soil.

In regard to the decrease in exchange capacity as a result of treatment (Table 2), the following general tentative conclusions were drawn from study of the test results shown in Tables 2 and 2a:

1. The electroösmotic and electrochemical methods of stabilization of soil cause not only a reduction in the moisture content of the soil but, at the same time, bring about definite changes in physicochemical properties of the material and possible changes in the structure of the clay particles. Therefore, these changes in physicochemical properties are also responsible for the improved physical properties of the material.

2. The decrease in exchange capacity, as presented in Table 2, should not be interpreted as the destruction of clay minerals at 35 volts, but rather as a chemical phenomenon which occurs during stabilization.

3. The author believes the destruction of clay particles will not occur unless a high voltage is used for an extended period of time. (Example, Granby Pump Canal soil at 100 volts, period 152 hr.)

4. The Granby Pump Canal soil contained a negligible amount of organic matter and no actual analysis of this material was made. Organic matter, if present in sufficient amounts, can influence the total base exchange capacity of soil during electric treatment. The author is glad that this point was brought out in the discussion.

In closing, it can be stated that a study of the electroösmotic and electrochemical results of different investigators, as well as the results obtained by the author, indicate that for a successful and economical application of the methods to achieve stabilization of fine-grained soil, the following information and investigations are necessary: (1) Determine the elevation of water table in the field or investigate the source of water producing the unstable and undesirable conditions of the soils in question; (2) determine the field density and moisture content of soil; and (3) obtain a representative undisturbed sample of each type of material to be treated.

The following laboratory tests and determinations should be made on these samples: (1) Physical and physicochemical properties of the soil prior to and after electrical or electrochemical treatment; (2) determination of the quantity of extracted water and electrical power requirement per unit volume of the soil; and (3) type, concentration, and quantity of a chemical solution or mixture of solutions needed per unit volume of the material to produce "permanent" stabilization of soil.

The above investigations should include the petrographic, chemical, and soil mechanics studies.