Electro-Osmotic Consolidation—Its Effects on Soft Soils

Consolidation Electro-Osmotique—Ses Effets sur les Sols Mous

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SYNOPSIS Consolidation by electro-osmosis and the effect of this consolidation on the strength of saturated soft clay (kaolinite) was determined experimentally under conditions where electro-chemical effects were minor. Pore pressure distributions, voltage distributions, current, and volumetric strains were measured as functions of time. It was found that electrically-induced negative pore water pressures are equivalent in consolidation to directly applied stresses of the same magnitude.

Previously available theory based on the assumption of constant soil properties underpredicts the amount and overpredicts the rate of consolidation by electro-osmosis, owing primarily to the substantial decrease in hydraulic permeability during treatment. In the absence of electro-chemical effects the relationship between water content (or void ratio) and undrained shear strength is the same irrespective of whether consolidation is caused by direct loading or electro-osmosis. It should be noted, however, that after removal of the electrical field a clay will be overconsolidated relative to the in situ effective stresses.

INTRODUCTION

Under controlled drainage conditions, negative pore water pressure can be induced by the action of electro-osmosis, and consolidation may occur, leading to changes in the stress-strain and strength characteristics of soils. In soft soils these changes can be sufficient to stabilize the soil for engineering purposes (Casagrande, 1935, 1957; Tamez and Flamand, 1959, Eide and Eggestad, 1963; Bjerrum, Moum and Eide, 1967; Fetzer, 1967; Chappell and Burton, 1975; and Wan and Mitchell, 1976).

The mechanism of electro-osmotic consolidation has been explained by the development of negative pore pressures in an electric field, but the contribution of such consolidation to the development of shear strength increases in soft soils has not been consistently accounted for quantitatively.

This paper reports the results of a laboratory investigation of soft, normally consolidated clay. The measured shear strength increases can be related to conventional e-log p and moisture content-shear strength relationships. A general mathematical theory for electro-osmotic consolidation can be formulated from the physics of electrical and water flows and the continuity requirement. Settlement analysis is discussed in relation to the laboratory test results and field observations.

EXPERIMENTAL INVESTIGATION

To evaluate the stress-strain and strength changes caused by electro-osmotic consolidation, laboratory tests on remolded kaolinite (Hydrite UF) were performed using a special consolidation box (Wan and Mitchell, 1975) and an oedometer modified for electro-osmotic consolidation as shown by Fig. 1. The selection of materials was such that the observed behavior was essentially free of electrochemical effects.

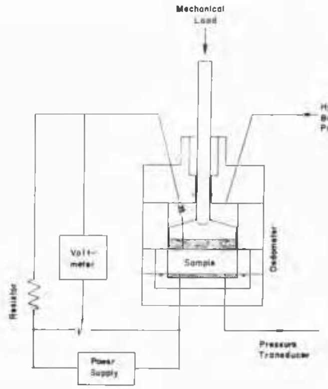


FIG. 1 SCHEMATIC DIAGRAM OF A BACK-PRESSURE OEDOMETER MODIFIED FOR CONSOLIDATION BY ELECTRO-OSMOSIS

Electro-osmotic Consolidation in Oedometer

Figure 2 shows the e-log p curve for a soil sample first consolidated from 0.5 to 1.0 kg/cm^2 by direct load consolidation. Then holding the applied pressure at 1.0 kg/cm^2, a voltage gradient of 3 volt/cm was imposed across the sample, and the consolidation was observed. After the consolidation was completed, the voltage gradient was removed. A direct stress of 4.0 kg/cm^2 was then applied and held constant until equilibrium was attained. Finally a voltage gradient of 2.5 volt/cm was applied, and consolidation was measured. In this and in other tests the application of direct loading stress increments following electro-osmotic consolidation led to re-establishment of the virgin compression curve corresponding to direct loading only.

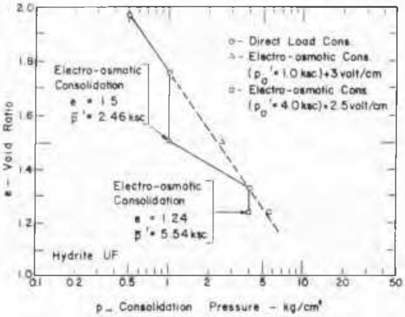


FIG. 2 CONSOLIDATION OF KAOLINITE BY DIRECT LOADING AND BY ELECTRO-OSMOSIS

Rate and Magnitude of Electro-osmotic Consolidation in Normally Consolidated Soil

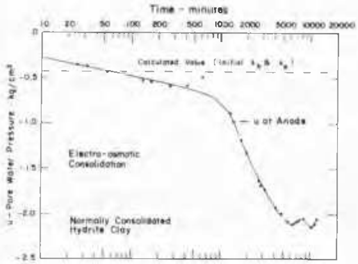
Soils that require stabilization by preconsolidation are usually soft. The magnitude of effective stress induced and the rate of consolidation caused by electro-osmosis in normally consolidated soil were tested in a consolidation box simulating one dimensional consolidation (Wan and Mitchell, 1975).

Figures 3, 4 and 5 show negative pore water pressure measured at the anode u_a, current density, and volumetric strains versus time for electro-osmotic consolidation of normally consolidated kaolinite. The values of hydraulic permeability k_h and electro-osmotic permeability k_e, Fig. 6, were measured before the electro-osmotic consolidation tests, and they were used to derive the theoretical value of $u_a = -(k_e/k_h)\,\gamma_w V_a$, where γ_w is the unit weight of water and V_a is the voltage at the anode (Wan and Mitchell, 1976). It can be seen that values of u_a based on the initial values of k_h and k_e were substantially less than the final values of u_a in all tests.

Typical distributions of u and V across the sample at different times are shown in Fig. 7. It was noted that there was a temporary effective stress reduction near the cathode at the beginning of the test, caused perhaps by water flow towards the cathode at a rate faster than it could be drained. This means a temporary loss of strength which can be of significance especially in very soft soil (Bjerrum, Moum and Eide, 1967).

In all tests, current density was constant during the initial part of the test, then increased slightly at approximately the time when the value of u_a reached the theoretical maximum value, based on k_h and k_e at the start of the test. After this increase, current density dropped to only a fraction of its initial value by the time u_a reached its maximum negative value.

(a) Negative Pore Water Pressure Measured at Anode



(b) Volumetric Strain and Current Density

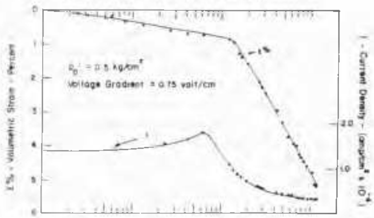
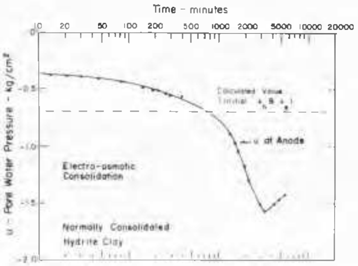


FIG. 3 NEGATIVE PORE WATER PRESSURE MEASURED AT ANODE, VOLUMETRIC STRAIN AND CURRENT DENSITY VS. TIME (p_o' = 0.5 kg/cm²)

(a) Negative Pore Water Pressure Measured at Anode.



(b) Volumetric Strain and Current Density

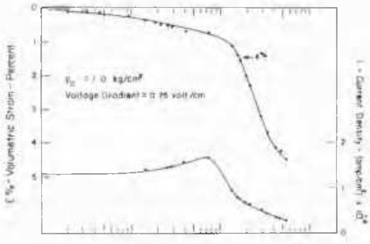
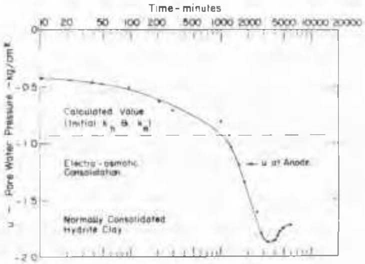


FIG. 4 NEGATIVE PORE WATER PRESSURE MEASURED AT ANODE, VOLUMETRIC STRAIN AND CURRENT DENSITY VS. TIME (p_o' = 1.0 kg/cm²)

(a) Negative Pore Water Pressure Measured at Anode



(b) Volumetric Strain and Current Density

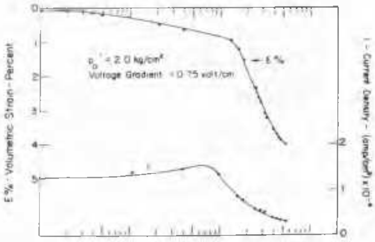


FIG. 5 NEGATIVE PORE WATER PRESSURE MEASURED AT ANODE, VOLUMETRIC STRAIN AND CURRENT DENSITY VS. TIME $(p_o' = 2.0\ \text{kg/cm}^2)$

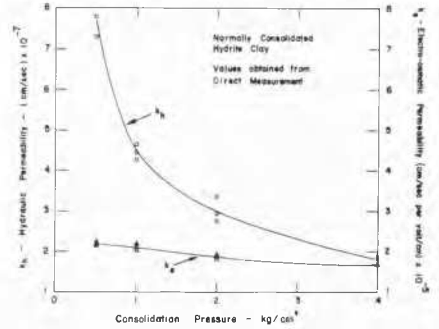
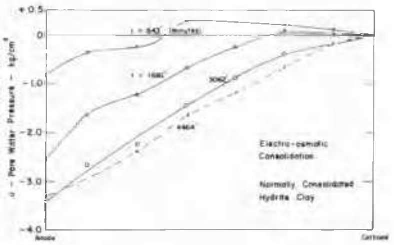


FIG. 6 HYDRAULIC AND ELECTRO-OSMOTIC PERMEABILITY VALUES AS A FUNCTION OF CONSOLIDATION PRESSURE FOR KAOLINITE

It may be postulated that the actual negative pore pressure exceeds the predicted value based on the original values of k_h and k_e, because as the soft soil consolidates, the value of k_h decreases much more than k_e (see Fig. 6), thus causing development of greater negative u, so more water is drained out of the system. The decreases in current density that accompany the development of large negative pore pressures and volumetric strains can be attributed to increased electrical resistance.

(a) Pore Water Pressure Distribution



(b) Voltage Distribution

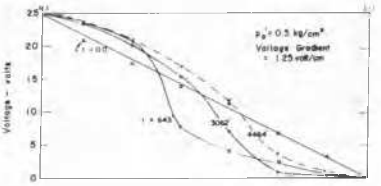


FIG. 7 PORE PRESSURE AND VOLTAGE DISTRIBUTIONS BETWEEN ANODE AND CATHODE AT DIFFERENT TIMES DURING CONSOLIDATION BY ELECTRO-OSMOSIS

Curve A in Fig. 8 represents the predicted time-settlement relationship for electro-osmotic consolidation based on the initial values of k_h and k_e, and assuming that they remain constant, using the theory developed by Esrig (1968) and Wan and Mitchell (1976). Curve B represents the calculated time-settlement relationship if the final values of k_h and k_e are used. In soft soil, where k_h and k_e are changing gradually from the initial values to the final values during the consolidation process the time-settlement relationship is described by Curve C.

Initially Curve C is similar to A, but progressively approaches Curve B at later stages of electro-osmotic consolidation. The settlement magnitude defined by Curve C is always greater than that described by A, and the time required to develop the full value of C is longer than that for A. A similar argument would also hold for the development of excess negative pore pressure.

A GENERAL MATHEMATICAL THEORY FOR ELECTRO-OSMOTIC CONSOLIDATION

The electro-osmotic consolidation process involves two constituent flows--the water flow and the electric current flow. The total water flow is the sum of flows under hydraulic and electrical gradients. The electric current flow involves direct electric conduction and a streaming current composed of electrical charges transported by flowing water.

In previous investigations; e.g., Vey (1949), Kondner

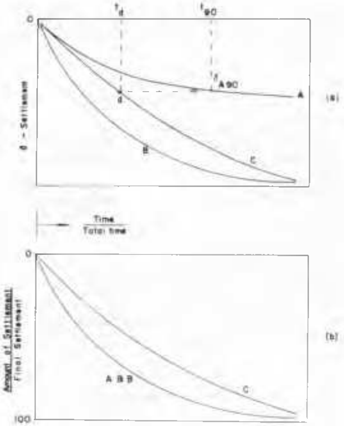


FIG. 8 TIME-RATE OF SETTLEMENT BY ELECTRO-OSMOSIS

and Boyer (1957), Schaad (1958), Mise (1961), Nicholls and Herbst (1967), Esrig (1968), and Wan and Mitchell (1976), variable water flow was considered but electrical flow was assumed constant. Changes in current, and variations of voltage distribution during electro-osmotic consolidation were observed in the experimental investigation described in the last section. The specific resistance was also found to affect the performance of the electro-osmotic consolidation. The permeability coefficients were observed to vary as the effective stress in the soil changes, and non-homogeneity developed during the electro-osmotic consolidation process. To take these factors into consideration, a general mathematical theory of electro-osmotic consolidation has been formulated for saturated soil.

The flow equations for water and electricity are

$$\vec{J}_w = -\frac{k_h}{\gamma_w}(\vec{\nabla}u) - k_e(\vec{\nabla}V) \qquad (1)$$

$$\vec{J}_e = -\frac{\sigma_h}{\gamma_w}(\vec{\nabla}u) - \sigma_e(\vec{\nabla}V) \qquad (2)$$

where $\vec{J}_w$ = flux density, or discharge velocity of water

$\vec{J}_e$ = current density

k_h = hydraulic permeability coefficient

k_e = electro-osmotic permeability

σ_e = electrical conductivity

h = streaming current conductivity

$\vec{\nabla} = i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}$.

The assumptions used for Equations (1) and (2) are

(1) The flux densities induced by a hydraulic gradient and a DC electrical potential can be superposed.

(2) There is no (or negligible) chemical gradient in the soil mass.

(3) The process occurs under isothermal conditions.

(4) The current density is low and the soil mass is reasonably dense, so that electrolysis and electrophoresis do not occur.

(5) The material is isotropic.

The law of conservation of mass (or charge) requires that the total mass (or charge) in any volume element of the system can only change if matter (or charge) flows into, or out of, the volume element. This leads to the continuity equations:

$$\vec{\nabla}\cdot(\vec{J}_w) + \frac{\partial \varepsilon}{\partial t} = 0 \qquad (3)$$

for water flow,

and
$$\vec{\nabla}\cdot(\vec{J}_e) + \frac{\partial T}{\partial t} = 0 \qquad (4)$$

for electrical flow,

where

ε = volumetric strain

T = charge density

Equation (3) is the usual consolidation equation, and Equation (4) in the absence of hydraulic coupling is one of Maxwell's field equations.

Substituting Equations (1) and (2) into Equations (3) and (4) respectively, we have

$$\vec{\nabla}\cdot\left(\frac{k_h}{\gamma_w}\vec{\nabla}u + k_e\vec{\nabla}V\right) = \frac{\partial \varepsilon}{\partial t} \qquad (5)$$

for water flow, and

$$\vec{\nabla}\cdot\left(\frac{\sigma_h}{\gamma_w}\vec{\nabla}u + \sigma_e\vec{\nabla}V\right) = \frac{\partial T}{\partial t} \qquad (6)$$

for electrical flow. This set of two differential equations is a general mathematical model that describes electro-osmotic consolidation for cases where properties vary during the process.

Beside introduction of appropriate initial and boundary conditions, additional information required to solve Equations (5) and (6) includes the values of the coefficients as well as the relationships between δu, $\delta\varepsilon$, δV and δT. The relationships between δu and $\delta\varepsilon$, k_h and k_e due to direct loading consolidation can be derived from the experimental data. The relationships between δu and δT can also be obtained. Experimental techniques to relate σ_e, σ_h, k_h, k_e and δT, to the state parameters u and V, resulting from electro-osmotic consolidation need to be established. While the formulation of all these relationships would require many tests, some simplifications might be made through the theory of irreversible thermodynamics, which correlates the streaming current conductivity to the electro-osmotic permeability (Katchalsky and Curran, 1965; Olsen, 1968; and Gray and Mitchell, 1967).

UNDRAINED SHEAR STRENGTH INCREASE

Figure 9 shows the undrained shear strength as a function of moisture content for Hydrite kaolinite after both electro-osmotic consolidation and direct loading consolidation. The corresponding values of effective consolidation pressure versus moisture content are plotted in Fig. 10. All data fall into a very narrowly banded region in both of these figures, and no distinction can be made between the values corresponding to the two types of consolidation. This agrees with the findings obtained in the oedometer tests that points on the e-log p diagram obtained from electro-osmotic consolidation lie very close to the virgin curve established by direct loading consolidation, as can be seen in Figs. 2 and 10.

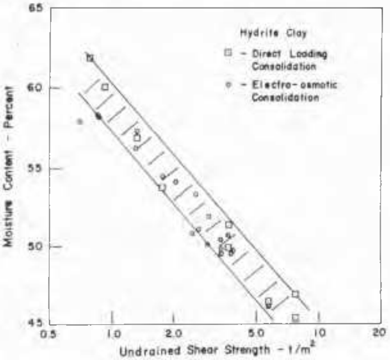


FIG. 9 UNDRAINED SHEAR STRENGTH VS. MOISTURE CONTENT RELATIONSHIP FOR KAOLINITE CONSOLIDATED BY DIRECT LOADING AND BY ELECTRO-OSMOSIS

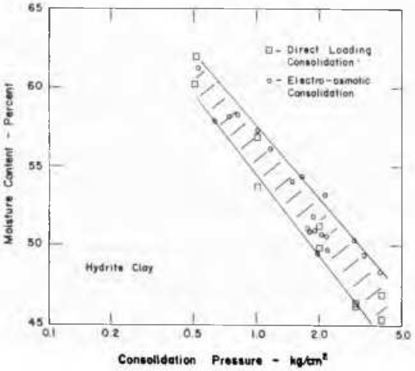


FIG. 10 MOISTURE CONTENT VS. CONSOLIDATION PRESSURE RELATIONSHIP FOR KAOLINITE CONSOLIDATED BY DIRECT LOADING AND BY ELECTRO-OSMOSIS

Figure 11 shows compression and rebound curves and their associated undrained shear strength curve as functions of moisture content or void ratio for a saturated soil. Normal consolidation is along the path defined by Points a, b, c and d, and a', b', c' and d' define the corresponding undrained shear strength s_u.

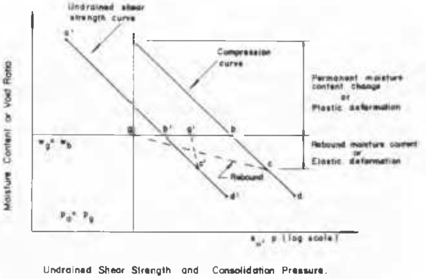


FIG. 11 STRENGTH, CONSOLIDATION PRESSURE, AND MOISTURE CONTENT RELATIONSHIPS FOR NORMALLY CONSOLIDATED CLAY

Electro-osmotic consolidation is a prestressing process; at the termination of electrical treatment the effective stress gained during the electro-osmotic consolidation relaxes gradually and some rebound occurs. The corresponding changes in moisture content and strength are shown by paths c-g and c'-g' in Fig. 11.

For soils that are relatively incompressible the shear strength after rebound is not significantly higher than before the electro-osmotic treatment. Medium to dense non-cohesive soils and heavily overconsolidated cohesive soils are in this category. There is no cohesion developed in noncohesive soils by electro-osmotic consolidation. For heavily overconsolidated cohesive soil reloading and rebound occur along almost the same path on an e-log p diagram.

As can be seen in Fig. 11 the actual difference in shear strength values between b' and g' depends on the overconsolidation ratio, and on the type of soil. If the overconsolidation effect were neglected, this part of the shear strength increase caused by electro-osmotic consolidation and rebound could erroneously be attributed to electrochemical hardening.

SETTLEMENT ANALYSIS

Consolidation settlement occurs as a result of volumetric strains caused by effective stress increases. In a saturated soil, both a reduction of excess positive pore water pressure as in direct loading consolidation, and an increase of excess negative pore water pressure as in electro-osmotic consolidation can produce effective stress increases. Figs. 2 and 10 show that the results obtained from electro-osmotic consolidation lie on or near the virgin compression curves produced by direct loading consolidation. In a field case record, Bjerrum, Moum and Eide (1967) report that at the initial stages the flow of water measured was in fair agreement with the amount predicted and corresponded closely to the observed rate of settlement measured at the end of the 120 days' treatment.

These observations suggest that there is no significant difference in the final volumetric strains derived from direct loading or electro-osmotic consolidation. Therefore, methods for estimating consolidation settlement on the basis of excess pore pressure dissipation which are suitable for direct loading consolidation should also be applicable to electro-osmotic consolidation.

CONCLUSIONS

The data and analyses presented in this paper lead to the following conclusions relative to the consolidation and strength changes associated with the electro-osmotic treatment of normally consolidated, saturated soft clays in the absence of electro-chemical changes.

1. Electrically induced negative pore water pressures are responsible for consolidation by electro-osmosis. The application of direct loading stress increments following electro-osmotic consolidation leads to reestablishment of the virgin compression curve corresponding to direct loading only.
2. Simple electro-osmotic consolidation theory as developed by Esrig (1968), Wan and Mitchell (1976), and others under-predicts the amount and over-predicts the rate of consolidation. The main factor responsible for this is the large decrease in hydraulic permeability k_h in relation to only a slight decrease in the electro-osmotic permeability k_e accompanying consolidation of a soft clay.
3. A general formulation for the rate of consolidation which accounts for variable soil properties and voltage distributions during the process has been made, but its usefulness is presently limited by lack of specific relationships between conductivity properties and the state parameters pore pressure and voltage.
4. In the absence of electro-chemical effects the relationship between water content (void ratio) and undrained shear strength is the same irrespective of whether consolidation is caused by direct loading or electro-osmosis.
5. After removal of the electrical field a clay will be overconsolidated relative to the in situ effective stress. The increased strength owing to this overconsolidation should not be attributed to electrochemical hardening.

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