Research on the Use of Electro-Osmosis in The Stabilization of Fine-Grained Soils

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Previous application of electro-osmosis in the field of soil mechanics were primarily intended to increase the shear strength and stability of fine-grained soils to facilitate excavations and slope construction. The purpose of the present research was to investigate the basic phenomenon of electro-osmosis and to explore the feasibility of incorporating this method with the vertical sand drain method as an assistance in the consolidation of fine-grained soils for use in the field of highway construction.

Theoretical considerations of this combination of electro-osmosis and vertical sand drains (electro-drains) are presented.

To investigate the basic phenomenon of electro-osmosis and to obtain certain electrical characteristics of the soil needed in an electro-drain analysis, an instrument termed an electrosometer was constructed. Experimental results of this instrument, operating under various conditions, are also presented.

Relatively large-scale laboratory consolidation tests were conducted on a layer of swamp muck which was 2 ft in depth. These tests were conducted under a surcharge pressure, using the floating embankment, vertical sand drain, and electro-drain methods of stabilization. Comparisons between theoretical and observed values for both rate of settlement and rate of reduction of excess pore water pressure are given for each of these methods of stabilization. A comparison has been made of the effectiveness of the three methods. Some economic aspects of the problem are also discussed.

• THE MODERN TREND in highway construction frequently challenges the ingenuity of the highway designer. Placing relatively high fills on marshy terrain cannot be avoided if the exacting requirements of alignment and grade are to be satisfied and if economically feasible projects are to be developed. In recent years, the sand-drain method of stabilization has been applied frequently to this problem with a fair record of success. Its prime feature is the reduction of construction time while adequately satisfying the conditions of controlled foundation soil settlement and the exacting requirements of slope stability.

The phenomenon of electro-osmosis was first reported by Reuss in 1807 and quantitatively interpreted by Helmholtz in 1879. Endell and Hoffman (*12*) are credited with proposing it, in 1936, as a method for dewatering and hardening clays. The research reported in this paper was conducted to investigate the feasibility of incorporating this method with the sand-drain method. This study involves fundamental considerations of the phenomenon, as well as an account of experiments showing the comparison of the proposed method to floating embankment construction and normal sand-drain construction.

THEORETICAL CONSIDERATIONS

The ratio of horizontal to vertical permeability is an important parameter in the settlement rate of a fine-grained soil. This ratio may also have important effects on the rate of change of shear strength of the soil. By applying the principles of electro-osmosis, the ratio of horizontal to vertical permeability may be appreciably increased. Electro-drains, the use of electro-osmosis in conjunction with a system of vertical sand drains, may affect the construction procedure for stabilization in the following manner:

1. For a given spacing of sand drains, the application of electrical energy would reduce the period of settlement;
2. For a fixed period of settlement, the application of electrical energy would increase the spacing of sand drains; and
3. For a fixed period of settlement, the application of electrical energy may decrease the height of surcharge required, with a consequent reduction of the likelihood of a shear failure.

Electro-osmotic flow is directly analogous to hydraulic flow and is expressed by an equational form similar to Darcy's Law (*5*). While the velocity of flow of water through soils due to a hydraulic gradient is

$$v = k\ i \qquad (1)$$

the velocity of pore water flow due to an electrical gradient can be expressed as (*5*):

$$v_e = k_e\ E \qquad (2)$$

in which

v = velocity of flow in cm per sec., relative to a cross-sectional area of the soil, due to a hydraulic gradient;
k = coefficient of permeability, in cm per sec.;
i = hydraulic gradient;
v_e = velocity of flow, in cm per sec., relative to a cross-sectional area of the soil, due to an electrical gradient;
$k_e = \left(\frac{e}{1+e}\right)c_1$ = electro-osmotic coefficient of permeability, in sq cm per volt-sec.;
E = electrical gradient, in volts per cm = ratio of voltage across electrodes to the distance between electrodes;
e = void ratio of the soil; and
c_1 = a function of the fluid contained in the soil (*5*), assumed constant for the material tested.

In the electro-drain process, the arrangement of the electrodes is such that the cathodes are located with the vertical sand drains, thus causing a flow of water, due to electrical energy, in a radial direction towards the sand drains. Having both electrical and hydraulic gradients acting at the same time and vectorially in the same direction, the total velocity of pore water flow may be expressed as:

$$v_t = v + v_e = k_h\ i + k_e\ E \qquad (3)$$

where k_h is the horizontal coefficient of permeability of the soil.

Using Darcy's Law, the total velocity may be expressed as:

$$v_t = k_{ht}\ i \qquad (4)$$

where k_{ht} is the total equivalent horizontal coefficient of permeability. The effect of electro-osmosis on the rate of settlement can be determined by substituting k_{ht} in the solution for the differential equation of consolidation for vertical sand drains. Because a form of the solution involves the non-dimensional time factor, T_r, the value of k_{ht} may be substituted in this expression, giving

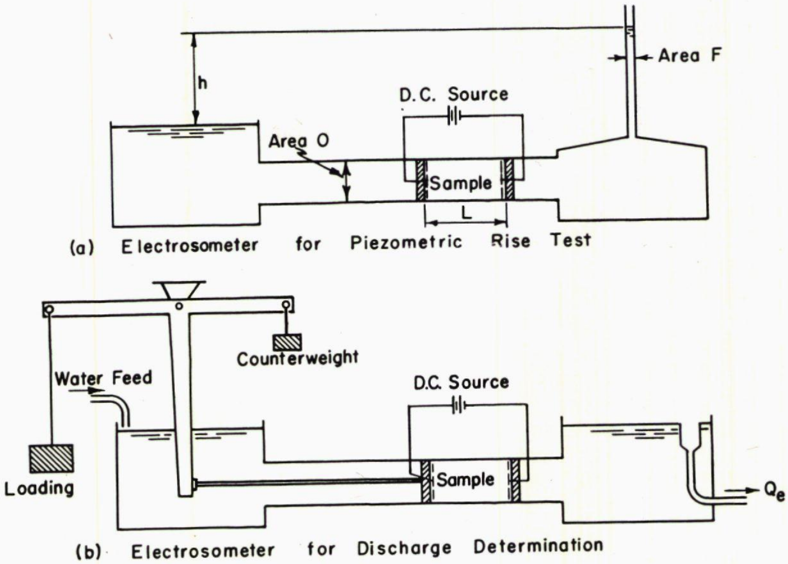
$$T_r = \frac{k_h\ (1+e)\ t}{\gamma_w\ a_v\ 4b^2} \times \frac{k_{ht}}{k_h} = \frac{c_r t}{4b^2} \times \frac{k_{ht}}{k_h} \qquad (5)$$

Settlements and excess hydrostatic pore pressures can then be obtained in the conventional manner (*3*).

EXPERIMENTATION

Electrosometer

To investigate the methods of obtaining the electrical characteristics of soils,



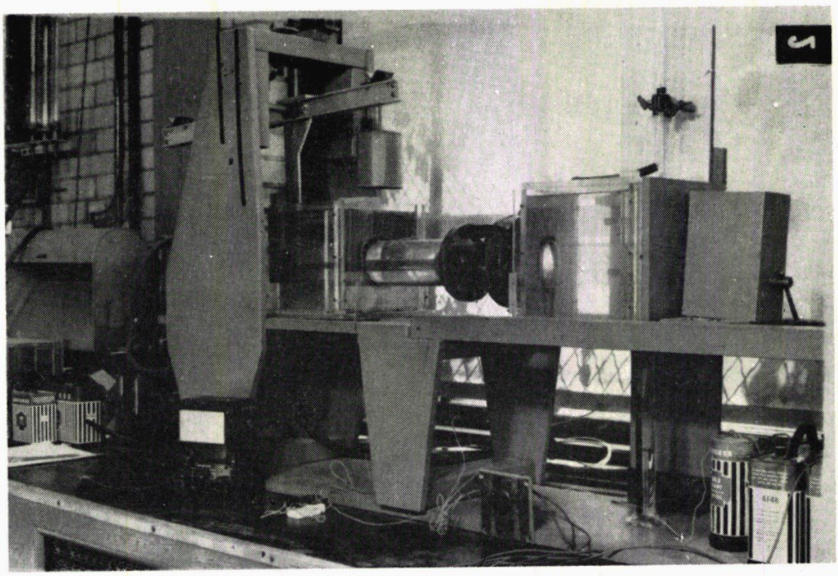


Figure 1. Schematic diagram and general view of electrosometer.

an instrument termed an electrosometer was constructed. This instrument was patterned after a model reported by Schaad and Haefeli (*9*), but was modified to permit additional investigation. Figure 1 shows a schematic diagram and photograph of this instrument. The electrosometer is useful in obtaining the electro-osmotic permeability as well as the conductivity of fine-grained soils.

When the electrosometer is set up for the piezometric rise test, the coefficient of electro-osmotic permeability may be expressed as:

$$k_e = \frac{k\,h}{V} \times \frac{\varepsilon^M}{(\varepsilon^M - 1)} \qquad (6)$$

where

ε = base of natural logarithms;
M = a substitution factor = kOt/FL;
F = cross-sectional area of the piezometric tube, in sq cm;
O = cross-section area of the soil sample, in sq cm;
h = rise of water in the piezometric tube, in cm;
t = time, in seconds;
L = length of sample, in cm;
k = hydraulic coefficient of permeability, in cm per sec; and
V = effective voltage across the sample.

It may be shown (*7*) that the maximum rise in the piezometric tube, h_{max}, can be expressed as:

$$h_{max.} = \frac{k_e}{k} V, \text{ at } t = \infty \qquad (7)$$

The electrosometer may also be utilized to study the rate of discharge with time. When utilized in this manner, the flow characteristics are governed by the relationship demonstrated by L. Casagrande (*6*):

$$Q_e = k_e\, E\, O \qquad (8)$$

in which

Q_e = discharge rate, in cc per sec;
k_e = electro-osmotic coefficient of permeability, in sq cm per volt-sec;
E = electrical potential gradient, in volts per cm; and
O = cross-sectional area of the sample, in sq cm.

This test determines k_e, in contrast to the ratio of k_e to k, which is determined using the piezometric rise test setup. By using both methods, it is possible to determine both k and k_e. The value of k can also be determined by a permeability test or from consolidation test data.

Because relatively short samples are used in the electrosometer, the voltage is kept low to maintain a potential gradient consistent with the range of practical applications and to prevent excessive electro-chemical effects in the soil. However, this causes complications. After experimentation with the electrosometer, using various voltages, it became apparent that when the external battery source was switched out of the circuit, the soil sample with its electrodes acted as a cell and produced a voltage that was opposite in direction to that of the battery. This opposite potential was called the residual voltage.

Simple tests were run for two electrodes immersed in tap water using systems of both similar and dissimilar metals. Both cells produced a residual voltage. Plating was observed in the cell of dissimilar metals, but an apparent hydrogen cell was produced by the system of similar metals. The hydrogen cell was due to a breakdown of the water molecules and the formation of clouds of charged ions around the electrodes.

Curves of current versus applied voltage were found to intersect the applied voltage axis at or near the residual voltage. This indicates zero current at an applied voltage equal to the residual voltage. Thus, the effective driving voltage is equal to the difference between the applied voltage, V_a, and the residual voltage, V_r, and can be expressed as

$$V = V_a - V_r \qquad (9)$$

Several tests were conducted to determine the variation of maximum residual voltage with different applied voltages and for various combinations of electrodes and electrolytes. The results of these tests are given in Figure 2.

The results of tests conducted at applied voltages of 6, 12, and 18 volts with the electrosometer set up for the piezometric rise method are presented in Figure 3. The shapes of these curves agree well with Eq. 6. Figure 4 gives the results obtained by testing a sample that

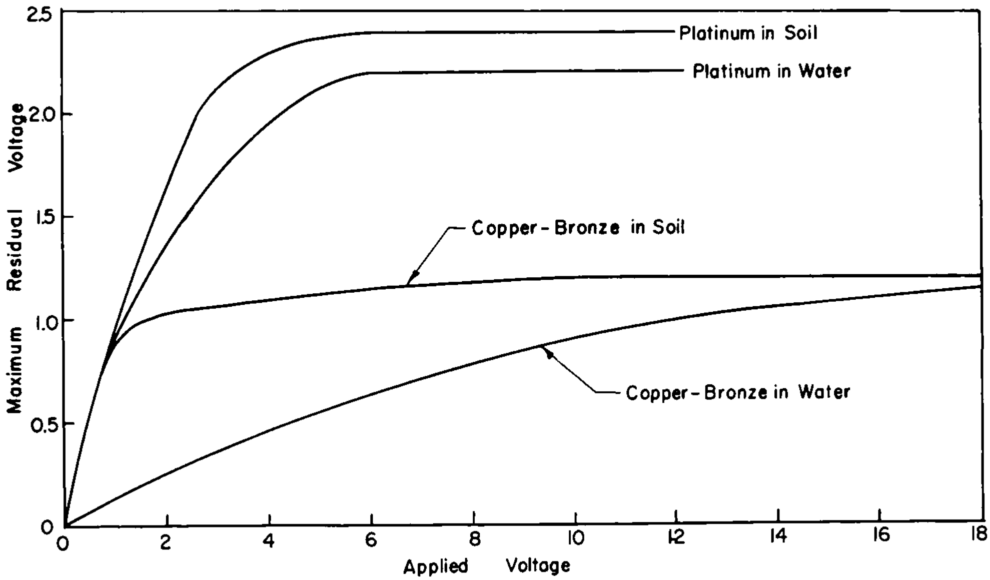


Figure 2. Electrode effect on residual voltage.

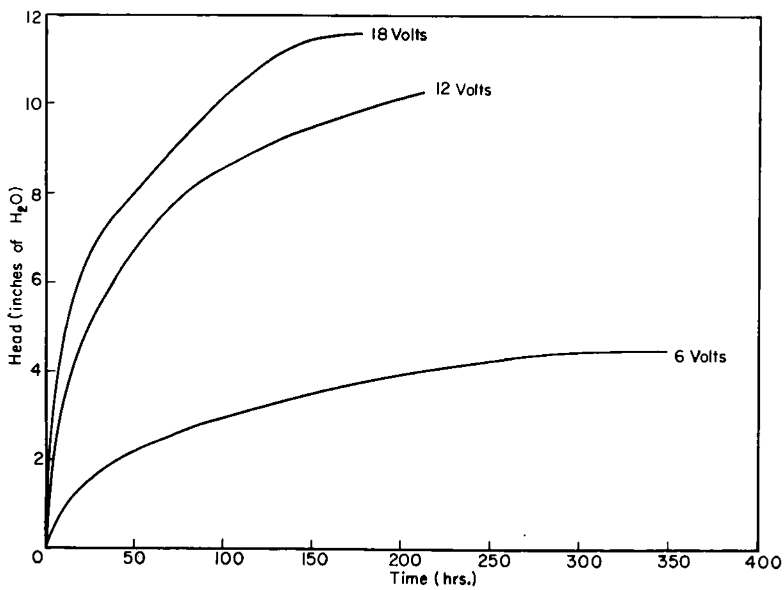


Figure 3. Electrosometer tests.

had been previously subjected to electro-osmosis, under an applied voltage of 12 volts. This graph shows that the piezometric rise built up to a maximum and then dropped off to a constant value. Genze, de Bruyn, and Jonstra (7) obtained results similar to this and theorized that the ratio of k_e to k did not remain a constant because of colloid-chemical and electro-chemical phenomena.

The electrosometer was set up for the rate of discharge method, but due to

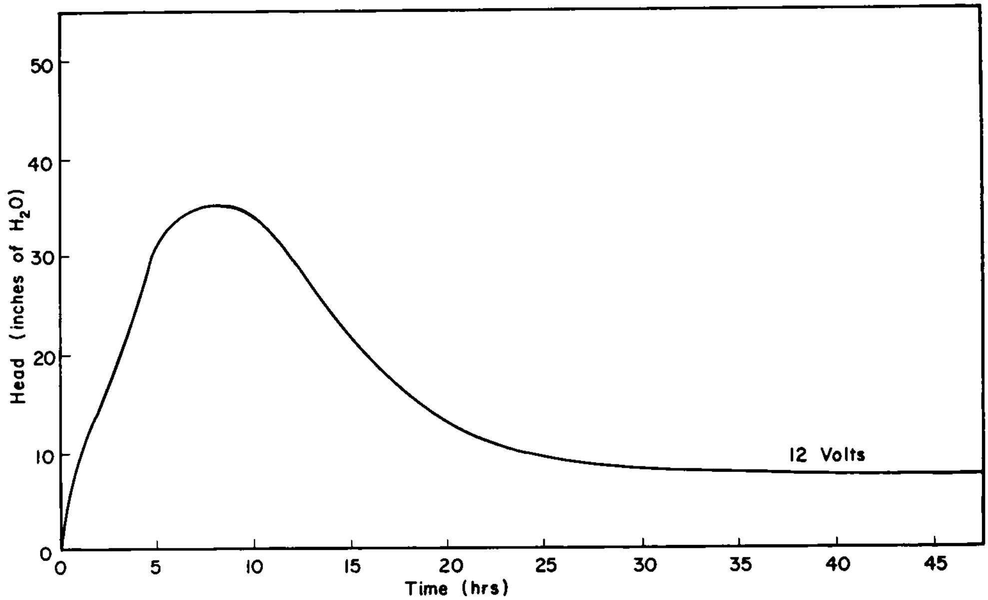


Figure 4. Electrosometer test.

menisci effects only the test presented in Figure 5 was successfully conducted. These tests also seemed to indicate that the ratio of k_e to k varies with time.

With the knowledge of horizontal to vertical hydraulic permeability as determined by soil analyses in the planning stage of a marsh stabilization job, additional knowledge is furnished by the ratio k_e to k which will permit an evaluation of the benefits to be derived from the possible addition of an electrical network.

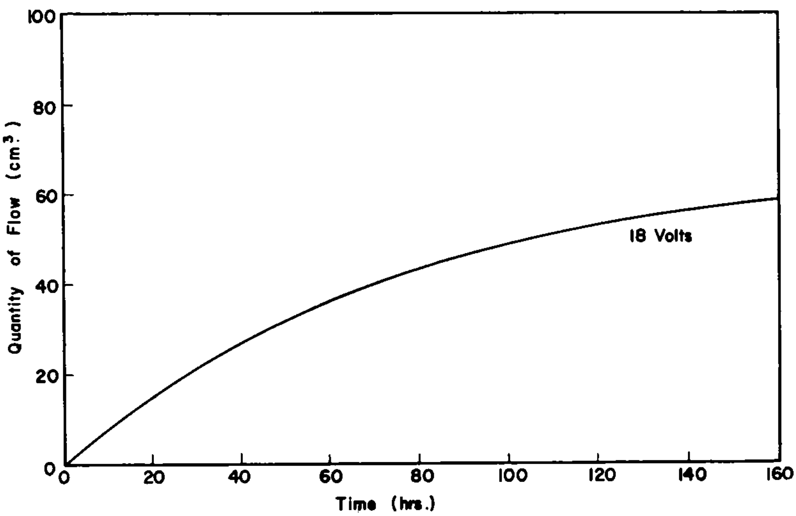


Figure 5. Electrosometer test.

Electro-Drain Study

Laboratory model studies were conducted to indicate the feasibility of incorporating an electro-drain net in a vertical sand drain system. These tests were run in a watertight box 4 ft by 1.5 ft in plan and 3 ft deep. The test samples were a selected Maryland swamp muck with a moisture content of approximately 100 percent, a plastic limit of 41 percent, a liquid limit of 56 percent, and a specific gravity of solids of 2.53.

Actual sand drains were not used in the experiments. These drains were simulated by hollow, porous, carborundum cylinders, which proved to be very useful. Electrodes used in the test chamber were brass rods arranged in the pattern indicated in Figure 6. The test chamber was equipped with pore pressure measurement devices as well as settlement scales. Loading was developed by concrete blocks (Figure 7) to an intensity of 0.225 kg per sq cm.

Typical conditions of a test were:

$k_z = k_h = 1.37 \times 10^{-7}$ cm per sec;
$c_z = c_r = 1.96 \times 10^{-4}$ sq cm per sec;
$a = 0.90$ inches = radius of drain;
$b = 11.72$ inches = tributary drainage radius;
$N = b/a = 12.94$;
$H = 22$ inches = thickness of test sample;
$p_z = 0.225$ kg per sq cm = loading intensity;
$i = 7.21$ = hydraulic gradient; and
$E = 0.42$ volts per cm = electrical gradient.

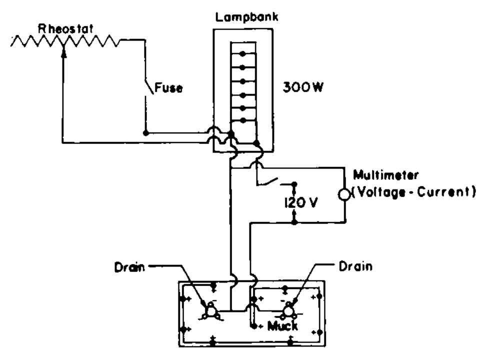


Figure 6. Electrical circuit for electro-drains.

The value of k_e was determined by electrosometer test to be 2.22×10^{-5} sq cm per volt-sec.

By using the relationships previously introduced, the following determinations may be made:

$$v_t = k_h i + k_e E = 103.08 \times 10^{-7} \text{ cm per sec;}$$

$$k_{ht} = \frac{v_t}{i} = 14.3 \times 10^{-7} \text{ cm per sec;}$$

$$T_r = \frac{c_r t}{4b^2} \times \frac{k_{ht}}{k_h} = \frac{t}{20};$$

$$T_z = \frac{c_z t}{H^2} = \frac{t}{184.5}; \text{ and}$$

$$\Delta H_{\text{ult.}} = 3.22 \text{ inches.}$$

The test period was 14 days, during which readings were taken of settlement and excess pore pressure reduction. Theoretical determinations of the settlement and pore pressure were made as a control and verification of the theory. The results of the test described are given in Figures 8 and 9. There is a remarkable correlation between theory and test, which promotes confidence in the electro-drain theory as well as the results of the electrosometer tests for determining permeability characteristics.

Comparison Tests

In addition to the electro-drain model studies just described, studies were also made in the test chamber for a conventional sand drain system and for a floating system without vertical drainage media. These tests served as a comparison of the efficiency of the drainage systems. It was not possible to completely control the settlement characteristics for each study. Consequently, for settlement comparison, all settlement curves were projected to a common reference based on an ultimate settlement, $\Delta H = 2.82$ inches. This comparison is shown in Figure 10,

Figure 7. Stabilization test.

from which it may be noted that the average percent consolidations at the end of 14 days for the tests were:

(a) Floating system, $U = 34$ percent;

(b) Sand drain system, $U = 51$ percent; and

(c) Electro-drain system, $U = 96$ percent.

Comparisons of theoretical and observed values of the settlement-time curves are very favorable and deviations are well within the range of experimental accuracy.

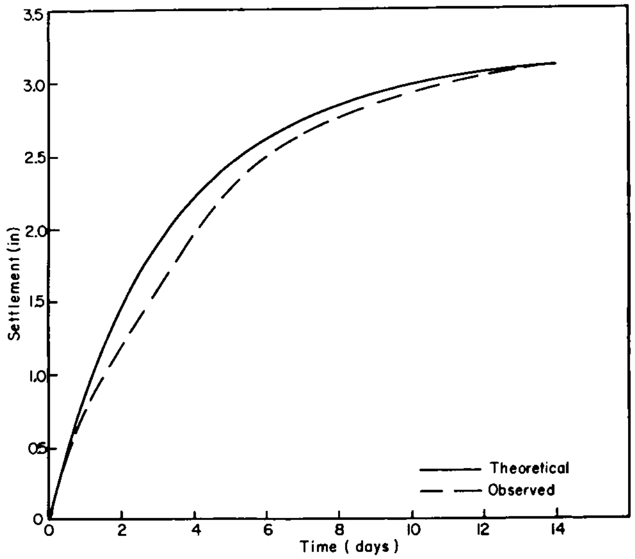


Figure 8. Electro-drain test.

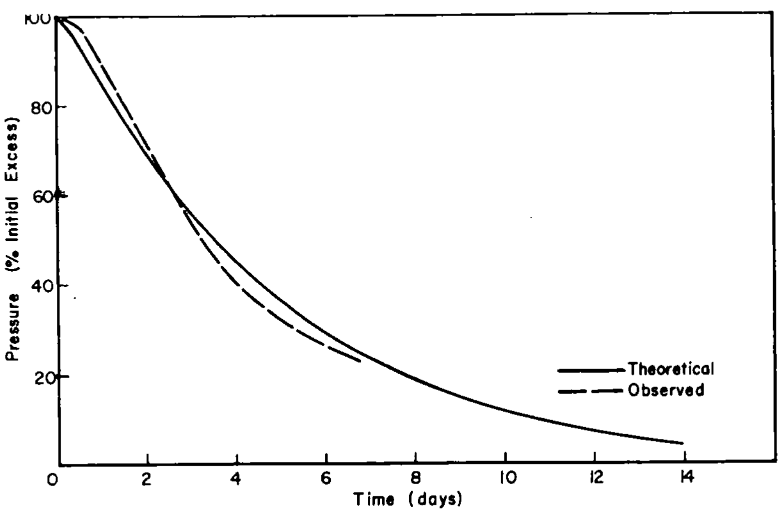


Figure 9. Electro-drain test.

CONCLUSIONS

Laboratory model studies using electro-drains indicate that good forecasts of settlement rates and excess pore pressure reductions can be made.

Any application of electro-drains must demonstrate an economic advantage to be considered. The studies reported in this paper have not been extensive enough in scope to justify a conclusive economic evaluation of the method. The electro-drain method will increase the horizontal permeability of the soil. This indicates beneficial changes in any one or combination of the following parameters: sand-drain size or spacing, height and rate of surcharge, and settlement period. The power requirements, as well as the cost of the electrical network, must be care-

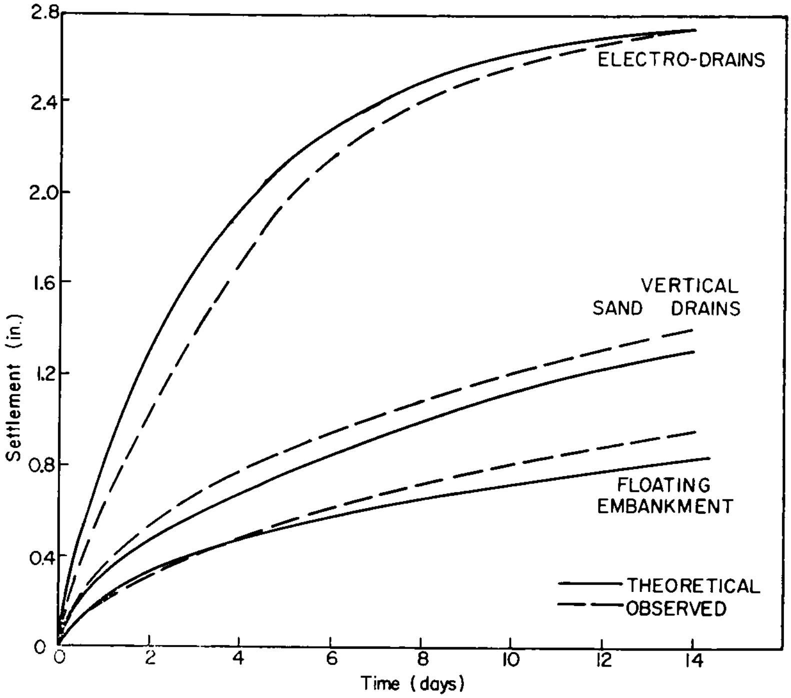


Figure 10. Settlement comparison.

fully weighed against the advantages. The application of electrical energy for short or intermittent periods indicates a decrease in power consumption while maintaining the favorable effects previously mentioned. For a given situation, such an evaluation should not only consider these parameters, but should include a charge applicable to the construction time that might be saved by using electro-drains.

Additional investigations could be pursued in the following areas. Experimentation should be conducted on a wide range of soil types to determine the influence of the ratio of k_c to k on the economy of the method. The effects of electrical energy on the rate of surcharge application, variation of shear strength, and geometry of the system merit additional investigation to determine optimum conditions for the economic application of electro-drains.

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