STATE-OF-THE-ART[1]

By Leo Casagrande[2], F.BSCES/ASCE

ABSTRACT

The purpose of this paper is to present a summary of the current theory and practical aspects of electro-osmosis, when applied to soils. Laboratory investigations of the parameters which control the effectiveness of electro-osmosis are discussed, and variations in these parameters are illustrated. Also discussed are details which should be considered during the design of field installations. Five case histories are briefly described, to serve as examples of the types of problems that could be effectively and economically solved by means of electro-osmosis.

INTRODUCTION

The phenomenon of electro-osmosis involves the transport of pore water in capillaries under the influence of an electric potential. It was initially observed more than 170 years ago (9), and is based on the fact that a direct-current electric potential

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[1]Presented to the Geotechnical Section of the BSCES/ASCE, on March 8, 1983

[2]Partner, Casagrande Consultants, Arlington, Mass.

causes any positive ions (cations) in the pore water to move
toward the cathode (-), and negative ions (anions) to move toward
the anode (+). Over the years, a number of theories have been
proposed to explain the mechanism by which the pore water is
transported, and a comprehensive review was presented by Gray
and Mitchell in 1967 (6). Esrig has also extensively studied the
mechanism of electro-osmosis, and reported his findings in a
series of reports prepared for the Corps of Engineers (4). Also,
the chemical processes that develop during electro-osmosis were
studied by Segall et al (10).

In my opinion, no one theory has yet been proven to be more
accurate than other theories for explaining the mechanism of
electro-osmosis. However, they are all basically variations of
the original Helmholtz theory (7), for electro-osmotic flow
through capillaries. When considering the structure of soils,
this theory would offer the following explanation: Positive and
negative ions are commonly present in soil-water systems. Because
soil particles are either positively or negatively charged, the
oppositely charged ions in the voids will concentrate adjacent
to the soil skeleton. Most soil particles have a negative charge
and will, therefore, attract positive ions; but some calcareous
soils (e.g. limestone, $CaCO_3$) have positively charged particles,
which would attract negative ions. When an electric potential
is applied to the soil, the ions are set in motion by the force
field. If an adequate number of ions along the capillary walls

(soil skeleton) move, they will drag along the adjacent water molecules. This moving film of water will cause the entire cross-section of the pore water to also move. In silts and clays, the pore water will be moved in the same direction as the boundary. layer; but in soils with larger voids, the central portion of the pore water may simply recirculate with the net result that water cannot be removed from such soils by electro-osmosis.

The rate of pore water movement within the voids will depend on the magnitude of the applied electric potential, the chemistry of the soil-water system, the size and shape of the pores, and on the relationship between the intergranular stress and the pore water tension. It is also affected by the availability of free water at the anode (for normal, negatively charged soil skeletons, where the water moves toward the cathode) to replenish the pore water. These variables were discussed in my 1952 paper (1).

Under normal circumstances, water is not available at the anode to replenish the pore water, and the water content of the deposit being treated will decrease, starting at the anode and progressing toward the cathode. This creates tensile stresses in the pore water, which result in consolidation and consequent strength increase of compressible clays and silts. However, in fine sands the tensile stresses are usually not adequate to effect densification of the soil skeleton, and electro-osmosis may result in only temporary strength increase due principally to the formation of capillary menisci. Electro-osmosis usually has little or no effect on coarser sands.

The development of tensile stresses in the pores of fine-grained cohesionless soils, such as silts, has the advantage that the strength can be increased sufficiently in a relatively short time to permit excavations with moderately steep slopes (e.g., 1 on 2.5). The stability can also be aided be designing the electrode installation such that the seepage forces will be directed away from the slope.

For most soils, adequate improvement can usually be achieved by using average potential gradients of less than 0.6 volts/cm. The water content of cohesive soils can be reduced to or slightly below the plastic limit near the anode, and the degree of reduction will become less toward the cathode. At the cathode, the water content may be reduced by only a relatively small amount, or not at all, depending on the length of treatment and other conditions. And if the clay is of a swelling type, i.e. if it contains such minerals as sodium bentonite which attract moisture, the water content near the cathode may actually increase to values considerably greater than prior to treatment. (You can imagine my consternation when this phenomenon developed during one of my early applications of electro-osmosis, for the stabilization of a railroad cut in Germany, in the early 1930's).

My experience has been that most effects of electro-osmosis are permanent, within the time frame of man-made structures. Once the strength of a cohesive soil or silt has been increased, there will usually be no significant reduction of strength, unless the material is substantially disturbed or remolded.

In order to establish the effectiveness of electro-osmosis and to permit the most economical design of field installations, typical samples should be tested in the laboratory. In some instances, it may also be advisable or necessary to carry out full-

scale tests in the field. The methods used to obtain the necessary
information, the analysis of this information, and its application
to the design of field installations and in-situ treatment, will
be discussed under the following headings.

LABORATORY TESTS

Laboratory tests are the most economical method for determining
the response of a soil to electro-osmosis treatment. One example
of a test set-up is shown in Fig. 1. Such tests can establish the
conductivity, coefficient of electro-osmotic permeability, change
in water content and Atterberg limits, and the increase in strength
of a test specimen. Also, variations in the pH of the discharge
water and its chemistry could be monitored. These variables will
be briefly discussed under the following sub-headings.

Conductivity. The conductivity is the reciprocal of the
resistivity, and is calculated by means of the following relationship:

$$\text{Conductivity, } \mathcal{E} = \frac{I \cdot L}{A \cdot E} \quad \text{amps/cm}^2 \text{ per volt/cm} \ . \ . \ . \ (1)$$

$$\text{where } I = \text{Electric current, amperes}$$
$$E = \text{DC voltage potential between electrodes, volts}$$
$$L = \text{Length of specimen, cm}$$
$$A = \text{Cross-sectional area of specimen normal to a}$$
$$\text{line between the electrodes, cm}^2$$

The conductivity may increase for a brief period after start
of treatment, and will then decrease as the water content is reduced
and other changes take place in the soil. The rate of decrease

depends on the initial liquidity index, the plasticity and
permeability of a soil, and the chemistry of the soil-water system.
The conductivity typically ranges from 5×10^{-4} to 5×10^{-5} amps/cm^2
per volt/cm, but it may vary considerably outside this range,
especially if the pore water contains highly charged ions. An
example of the change in conductivity during treatment is shown
by the solid curve in Fig. 2, which is the average of 15 tests
on samples of silty clay with low to medium plasticity.

Coefficient of Electro-Osmotic Permeability. The coefficient
of electro-osmotic permeability, k_e, is an indicator of how quickly
a soil can be dewatered, and it should not be confused with the
commonly-known coefficient of hydraulic permeability, k. The
magnitude of the electro-osmotic permeability is principally
dependent on the electric potential gradient, the chemistry of
the soil-water system, and the relationship between the pore water
tension and the intergranular stresses. Experience and theory
indicate that it is largely independent of the size of the pores (1).
This coefficient can be computed using the following relationship:

$$k_e = \frac{Q_e \cdot L}{A \cdot t_e \cdot E} \quad \text{cm/sec per volt/cm} \quad \ldots \ldots \ldots \text{(2)}$$

where Q_e = Volume of water discharged in time t_e, cm^3

L = Length of specimen, cm

A = Cross-sectional area of specimen, cm^2

t_e = Elapsed time during which Q_e is measured, sec.

E = DC voltage between electrodes, volts

The coefficient of electro-osmotic permeability initially
increases after the voltage is applied, but within a relatively
short time it will begin to decrease as the water content of the
soil begins to decrease. The decrease may also partially be the
result of corrosion and other insulating factors at the anode.
An example of the change in k_e during treatment is shown by the
dashed curve in Fig. 2, which is the average of 15 tests on samples
of silty clay. The average values for typical soils, including
sands, range from about $2x10^{-5}$ to $5x10^{-5}$ cm/sec per volt/cm.
Because the coefficient of hydraulic permeability for sands is
usually greater than this range, the pore water could recirculate
due to gravity stresses, and electro-osmosis would be ineffective.

Comparison of the coefficient of electro-osmotic permeability,
k_e, with the coefficient of hydraulic permeability, k, illustrates
why electro-osmosis is such a useful tool for dewatering fine-grained
soils. The quantity of water that can be moved through a soil
section in a given time, t, due to gravity consolidation stresses is

$$Q = k\ i\ A\ t \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (3)$$

where k = Hydraulic coefficient of permeability, cm/sec

       i = Hydraulic gradient = $\frac{h}{L}$, where h (cm) is the hydraulic
          head equivalent of the effective consolidation stress

     L = Length of drainage path, cm

    A = Cross-sectional area of drainage path, cm^2

By equating Q from Eq.(3) to Q_e from Eq.(2), one obtains the relationship

$$t = \frac{k_e \ i_e}{k \ i} \ t_e \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (4)$$

where $i_e = \frac{E}{L}$, the electric potential gradient, volts/cm.

If one assumes for a clay values of $k = 5 \times 10^{-8}$ cm/sec and $k_e = 4 \times 10^{-4}$ cm/sec per volt/cm, and an applied voltage gradient of $i_e = 0.5$ v/cm and an effective consolidation stress equivalent to a hydraulic gradient of $i = 10$, one can compute using Eq.(4) that the time required for an equal reduction in water content would be

$$t = 400 \ t_e$$

In other words, for the given assumptions, it would take 400 times as long to effect the same degree of improvement in a clay deposit by loading the surface, as it would by applying electro-osmosis.

Water Content and Atterberg Limits. Electro-osmosis not only reduces the water content of fine-grained soils, but usually also increases the liquid and plastic limits and the plasticity index of a clay, particularly near the anode. The magnitudes of these changes decrease towards the cathode. Near the cathode there may be little or no change in the water content and plasticity, and even a small decrease in the plasticity index may develop, depending on the length of treatment. An example of the range of changes in the plasticity indexes near the anode and cathode, due to electro-

osmosis treatment of 13 samples of silty clay for various periods
of time, is shown in Fig. 3.

An increase in the Atterberg limits means that the water
content does not have to be reduced as much as would be necessary
without electro-osmosis, to obtain an equal increase in strength.
Therefore, one must view the water content in relation to the range
of plasticity, i.e. in terms of the liquidity index. Near the anode
the liquidity index can typically be reduced to zero (water content
at the plastic limit) or even to negative values with sufficiently
long treatment. The liquidity index of treated samples will
gradually increase toward the cathode, and near the cathode there
may be little or no change in the liquidity index, depending on
the characteristics of the soil being treated and on the time of
treatment. Fig. 4 shows the ranges of change in liquidity index
near the anode and cathode, due to treatment of the 13 samples
of silty clay represented by Fig. 3. The water contents of these
samples, which were initially considerably above the liquid limit,
were reduced to approximately the plastic limit near the anode and
to somewhat below the liquid limit near the cathode.

It should be noted that the plasticity of cohesive soils does
not always increase. For organic soils, I have observed a decrease
in the liquid limit with little change in the plastic limit.
However, because of the large void ratio and compressibility of
organic soils, the water content could be easily reduced to
adequately improve their strength properties.

Strength Increase. The strength of electro-osmotically
treated soils increases as a result of three factors: (1) Decrease
in water content and consequent consolidation; (2) formation of
menisci in the soil voids; and (3) bonding and/or cementation of
the soil particles. After one to two weeks of treatment, laboratory
samples of very soft clay have become so hard near the anode that
the material had the characteristics of a soft rock. The increase
in strength gradually becomes less toward the cathode, and at the
cathode there may be little or no strength increase. For samples
treated in an unconfined state, the strength at the cathode may
actually decrease due to swelling, but this would normally not
happen in situ because of the overburden stress. The results of
shear strength tests made near the anode and cathode, for samples
of initially very soft, low to medium plastic clay treated for
various lengths of time, are shown in Fig. 5. At the end of
treatment, many of the strength values near the anode exceeded
the 2.5 ton/sq ft capacity of the Torvane measuring device.

The strength of soils with high quartz contents may also
be increased due to bonding of the particles. When amorphous
quartz is exposed to pH values in the basic range, and particularly
values greater than 9 (as are known to develop during electro-
osmosis treatment - see next sub-heading), it begins to dissolve.
Recrystallization of this quartz will form bonds between soil
particles. Such bonding was proposed by Whalley (12), to explain
the unexpectedly high strength of glacial till deposits and

quickclays with naturally high pH values. The fact that bonding

developes during electro-osmosis is evidenced by a shift in the

grain size distributions of quartz soils before and after treatment.

One example is presented in Fig. 6, which shows the grain size

curves for a fine quartz sand before treatment, and after 5 days

and 9 days of treatment with a voltage gradient of 1.3 volts/cm.

High pH values of the pore water also means that alkaline

chemicals may be available for cementation of soil particles and

for deposition in the voids, especially near the cathode. I have

occasionally observed this development both in the laboratory and

in the field, and it can significantly increase the strength of

a deposit. Cementation may also develop as a result of ions

released by corrosion of the anode. Aluminum ions form particularly

strong interparticle bonds.

The strength of relatively pervious soils could also be

improved by the introduction of chemicals at the electrodes. The

chemical ions would be transported as a result of the electric

potential and by the movement of pore water. They would act not

only to bond or cement soil particles, but also to reduce the

size of the voids due to infilling.

Electro-osmosis also improves the consolidation characteristics

of cohesive soils, especially near the anode. An example of this

is illustrated by the consolidation curves shown in Fig. 7, for a

silty clay of low to medium plasticity. The preconsolidation

pressure near the anode increased from an initial value of about

1 ton/sq ft, to almost 6 tons/sq ft after only 40 hours of treatment
with a potential gradient of about 0.5 volts/cm.

pH and Chemistry of Discharge Water. For most soils, where
positive ions are moved toward the cathode during electro-osmosis,
the pH (hydrogen-ion concentration) of the discharge water will
be higher than that of the pore water in the untreated soil.
Usually, the pH of the discharge will be greater than 7, i.e. it
will be basic, and pH values of 12 to 13 should not be unexpected.
An explanation for this pH increase was proposed by Segall et al
(10). The pH will increase during the initial stages of treatment,
and may then decrease as the rate of discharge decreases. An
example of the change in pH during treatment of a sample of low
to medium plastic silty clay is shown in Fig. 8. The pH of water
removed from the sample prior to start of electro-osmosis was 7.6.

It may occasionally be of interest to determine and monitor
the chemical content of the water being discharged, especially if
electro-osmosis is being used to dewater waste ponds from industrial
processes. However, this requires specialized knowledge of
chemistry and testing equipment that is not normally found in a
soil mechanics laboratory. Under normal circumstances, the chemical
content of the discharge water should be of little consequence from
an ecological standpoint.

ANALYSIS OF LABORATORY RESULTS FOR IN-SITU APPLICATIONS

For an assumed electrode spacing in the field, and for assumed lengths of the electrodes, one can estimate by means of the following relationship the total electric current that will be required for in-situ treatment:

$$I_t = n \, c \, S \, \mathcal{E} \, \frac{E}{L} \quad \ldots \ldots \ldots \ldots \ldots \quad (5)$$

where I_t = Total amount of current required to energize the in-situ electrode installation, amperes

      n = Number of electrode pairs energized

      c = Efficiency factor (for one row of alternate anodes and cathodes, i.e. two anodes serving each cathode, c = 0.8 to 0.9; for two or more parallel rows, each cathode will be served by more than two anodes, and c can decrease to 0.6 or lower)

      S = Embedded surface area of a typical in-situ electrode, cm^2

      $\mathcal{E}$ = Electric conductivity of material being treated, determined from laboratory or in-situ testing, $amps/cm^2$ per volt/cm

      E = Voltage to be applied in the field, volts

      L = Distance from anodes to cathodes, cm

When trying to predict the electric current requirements and effectiveness of a field installation, one must always keep in mind the limitations of trying to predict the behavior of an in-situ soil

deposit on the basis of laboratory tests. A number of factors
could either increase or decrease the effectiveness of the field
installation as compared to the laboratory results. For example,
the field effectiveness could be greater due to the overburden
stresses, or it could be less due to stratification or fissuring
of the deposit being treated, or due to recirculation of groundwater.
Also, increasing resistance around the anode and the height of the
water level at the cathodes could affect the results. Such variables
make it difficult to predict with reasonable accuracy the length of
time that will be required to effect a desired degree of in-situ
improvement. Experience is the best tool for making such predictions.

DESIGN CONSIDERATIONS FOR FIELD INSTALLATIONS

Under the following sub-headings, a number of items are
discussed that must be considered when designing a field installation.

General. There is usually a substantial voltage drop within
a short distance from the electrodes. Therefore, the voltage gradient
over the major portion of the distance between electrodes is
significantly smaller than would be computed by dividing the applied
voltage by the distance between electrodes. Attempts to increase
this central gradient by increasing the applied voltage may be only
partially successful, because the percentage of the voltage that is
"dropped" near the electrodes increases with increasing voltage.
For this reason, and for safety reasons, the applied voltage is
usually limited to 160 volts. For a 10-ft electrode spacing, this
will provide an average potential gradient of about 0.5 volts/cm.

The applied voltage may also have to be limited to prevent
excessive heating of soils with high conductivities. Heating has
little or no beneficial effects from the standpoint of improving
the strength of a deposit, but consumes considerable energy. It
should therefore be minimized. For soils with high conductivity,
this can be achieved by applying relatively small average voltage
gradients (e.g. 0.1 to 0.2 volts/cm). However, if electro-osmosis
treatment is urgent, higher voltage gradients may have to be used
at the expense of wasted power. But it has been my experience that
many soils with high conductivities also have relatively high
coefficients of electro-osmotic permeability, which means that the
rate of improvement may be fairly rapid despite low voltage gradients.

One other factor that could have a significant bearing on the
electric current requirement and on the effectiveness of electro-
osmosis is the formation of an insulating zone around the anodes.
Such a zone may develop principally due to drying of the soil, which
not only increases its resistance, but also causes shrinkage of the
soil away from the electrode. The formation of gas at the electrodes,
due to hydrolysis, will also contribute to the insulating effect, .
particularly at the anode because the gas cannot escape as readily as
at the cathode. Another insulating layer may result from corrosion
of the anode. These developments do not always progress to such a
degree that they require special precautions. If necessary, they
can be counteracted with some degree of success by simply ponding
water on the ground surface around each anode.

Types of Electrodes. For the purpose of reducing the water
content of a natural soil deposit, steel electrodes are commonly
used. Because the anodes will normally corrode during treatment,
they may eventually have to be replaced, or extra-heavy sections
could be initially installed. Railroad rails have occasionally
been used as anodes, when available.

Aluminum anodes have the advantage that as they corrode,
the aluminum ions move toward the cathode and act to cement the
soil particles. Ions of steel have the same effect, but to a
much lesser degree.

If corrosion of the electrodes is expected to be extensive
during the proposed treatment period, it may be more economical
to install non-corroding carbon-based electrodes, such as a
combination of Duron and coke-breeze.

The cathodes generally do not corrode, but chemicals may be
deposited from the groundwater. Usually cathodes can consist of
relatively small steel sections, and often 1.5 to 2-inch diameter
steel pipe is used. Because water normally has to be removed at
the cathode, the pipe may be slotted or perforated. More commonly,
a slotted PVC plastic well-pipe is installed adjacent to the metal
cathode, and surrounded by a sand filter. The efficiency of cathode
wells that have become clogged by chemical deposits can often be
increased by treating the wells with an acid solution.

Pattern of Electrode Installation. The pattern of anodes and
cathodes will usually have to be tailored to specific applications.

For treatment of large unobstructed areas, a checkerboard pattern
of anodes and cathodes will in many instances provide the most
efficient installation. This pattern has the advantage that water
is being moved toward each cathode by four anodes. Any repeat-pattern
where there are more than four anodes for each cathode will result
in increased interference of the electric fields between electrodes,
and with a consequent decrease in efficiency. For the treatment of
slopes, or areas where slopes will be cut, the best design may
consist of parallel rows of anodes and cathodes. In this manner, the
seepage pressures can be directed away from the face of the slope.

   Depth of Electrode Embedment. This variable will depend on
the geologic boundaries of the deposit to be treated and on the
purpose of the installation. Usually the electrodes are installed
to the bottom of the weak deposit. However, if this deposit is
very thick, it may be adequate to treat only the upper portion.
If the top of the deposit to be treated is under water, or is
considerably below the groundwater level, the top of the electrodes
could be insulated. Jetting is often used to install electrodes.

   Spacing of Electrodes. The spacing of electrodes will depend
primarily on the design of the project and on the urgency of treatment.
It may also depend on the available electric power supply. Spacings
ranging from 30 ft to less than 10 ft have been used, but for the
majority of the projects with which I am familiar, the electrode
spacings were 10 to 20 ft. Theoretically, there is no limit to the

maximum spacing, if sufficient DC voltage is available to provide
the desired voltage gradient. However, the degree of the voltage
drop near the electrodes increases with increasing voltage, as
discussed previously, and it becomes uneconomical to use very large
spacings.

     For a given power supply, decreasing the electrode spacing will
increase the potential gradient, which will normally decrease the
required treatment time. On the other hand, it may sometimes be more
economical to install fewer electrodes by increasing the spacing,
but with the drawback that the treatment time will be lengthened.

     Electric Power Supply. Direct-current (DC) electric power is
required for electro-osmosis. It can be supplied either by means
of portable generators, including welding equipment, or from a
utility power plant. If only alternating-current (AC) power is
available, it would have to be converted to DC by means of rectifiers.
The applied voltage generally ranges between 60 and 160 volts, but
higher or lower voltages may be required or considered desirable
under special circumstances.

     The number of generators or rectifiers that will be required
will depend on the capacity of each unit and on the electric current
requirement for the total installation. A requirement of many
thousands of amps is not uncommon for reasonably large installations.
However, it is often possible to limit the required capacity by
treating the overall project in sections, rather than all at once.

Removal of Water at Cathodes. The maximum benefit from
electro-osmosis can be gained when the water level at the cathodes
is maintained at or near the bottom of the deposit being treated.
A number of different methods could be used to remove the water at
the cathode. If the normal groundwater level is near the ground
surface, the simplest solution is to allow the discharge to flow
freely from the top of the cathode well-pipe. This may require
some channeling to keep the water from short-circuiting to the
anodes. If the deposit being treated is underlain by a pervious
layer with a relatively low piezometric level, the cathodes could
be extended into that layer and the water would drain by gravity.
If such a pervious layer exists, but the piezometric level is too
high to permit natural gravity drainage, it may be possible to
lower the level by means of a number of deep pump wells. Another
alternative would be to remove the water by means of a vacuum
system attached to the top of the cathode wells, but this has the
limitation that the maximum drawdown is about 30 ft (under ideal
conditions). Still another effective, but relatively expensive
method is to install an eductor pipe in each cathode well and
remove the water by pumping.

Length of Treatment Time. Considerable experience is required
to predict with reasonable accuracy the length of time that will
be needed to achieve a desired degree of in-situ improvement. As
little as two weeks may be adequate for non-plastic soils, and as
long as one year may be required for certain clay soils.

The effectiveness of electro-osmosis can quickly be judged
of the basis of piezometer readings. In addition, the progress
of treatment should be evaluated by monitoring the rate of discharge
at the cathodes and the electric current consumption (amperage).
These variables will decrease as the treatment becomes less effective.
Methods of determining the strength increase include the testing
of samples from borings, and in-situ penetration and pressuremeter
tests.

APPLICATIONS OF ELECTRO-OSMOSIS

Electro-osmosis has been used successfully for a number of
different purposes: (1) Increasing the strength of weak deposits
to permit construction of an embankment or other structure;
(2) stabilization of landslides or excessive foundation deformations;
(3) increasing the strength of a weak deposit and/or controlling
seepage forces to permit excavation with relatively steep slopes;
(4) increasing the load capacity of steel friction piles;
(5) decreasing the water content of fine-grained materials in
disposal ponds; and (6) chemical cementation of granular soils by
electro-osmotic transport of a cementing agent introduced at the
electrodes.

All of the electro-osmosis projects with which I have been
associated in the United States and Canada have been carried out
by the Wellpoint Dewatering Corporation and by Loughney Dewatering,
Inc., which are both located in New York State. Several of these
projects are briefly described below.

West Branch Dam (Mahoning River, Northeastern Ohio). This is
an earth dam that was constucted during 1963-66, across the West
Branch of the Mahoning River, by the Corps of Engineers (5, 13).
It is several thousand feet long, and the central 1000-ft long
portion has a height of about 80 ft. The base width, including
berms, is about 800 ft, as seen in Fig. 9. The dam is underlain
by 60 ft of soft silty clay, which in turn is underlain by layers
of silt and sand (see Fig. 9). Three spillway conduits at the base
of the dam were monitored for deformation during construction of
the embankment. Just prior to completion of the embankment, large
deformations developed. The top of the embankment was subsequently
removed, and piezometers were installed. It was found that the
piezometric levels in the clay were considerably above the embankment.
Stability analyses indicated that the piezometric levels must be
immediately lowered, and electro-osmosis was chosen as being the
most suitable method for this purpose.

Electrodes were installed to the bottom of the clay deposit,
along the central 1000-ft long portion of the embankment. The
electrode spacing was 20 ft. Eight rows of electrodes were
installed along the crest, and six rows were installed along both
the upstream and downstream berms, as shown in Fig. 9. Details of
the electrodes are shown in Fig. 10. A partial view of the
completed installation on the downstream berm is shown in Fig. 11.

The power was supplied by 14 generators with capacities ranging
from 90 to 300 KW . The recommended voltage was 150 volts, but the

voltages of the available generators ranged from 60 to 150 volts
(0.10 to 0.25 volts/cm). The electrodes were energized progressively
as they were installed. When fully operational, the generators
supplied about 14,000 amps.

     The total elapsed time from the beginning to the end of
treatment was about 10 months. The decrease of the piezometric
level in the clay during the period of treatment is shown in
Fig. 12, for one of the piezometers. To the best of my knowledge,
there have been no further problems with deformation of this
embankment.

     Trans-Canada Highway Bridge, Little Pic River (Ontario, Canada).
This bridge was designed to be constructed on pile foundations.
During excavation of the east riverbank, to prepare the pier areas
for pile driving, several landslides developed (2, 8). Because it
was necessary to drive numerous steel H-piles through as much as
130 ft of loose, saturated silt, the designers decided to first
stabilize the slope by means of electro-osmosis. Laboratory tests
showed that the water content of the silt could be reduced by at
least 3%, and that substantial pore water tension could be developed
by application of 100 volts to electrodes at a spacing of 10 ft
(0.33 volts/cm). A general view of the electro-osmosis installation
is shown in Fig. 13; and Fig. 14 shows a row of cathodes that have
been partially exposed by subsequent excavation of a 1 on 1 slope.

     All treated slopes remained perfectly stable despite substantial
vibrations caused by pile driving. Furthermore, to the best of my

knowledge, there have been no signs of instability in the 25 years
since this project was completed.

     Canadian Pacific Railway Cut (Revelstoke, British Columbia).
The design of a second track along a mountain valley included a
several-thousand-foot long cut, up to about 50 ft deep, to permit
a lower grade than the existing track (3). Along the major portion
of this cut alignment, the subsurface conditions consisted of 5 to
10 ft of fibrous peat, underlain by 20 to 30 ft of very soft clayey
silt. This in turn was underlain by dense silt or bedrock. The
groundwater level was near the ground surface. Test excavations
in the field confirmed that these conditions would have necessitated
excavation slopes as flat as 1 on 10, and large volumes of granular
backfill. Laboratory tests indicated that electro-osmosis would be
very effective.

     The electro-osmosis installation consisted of four parallel
groups of electrodes along the alignment of the cut; each group
consisting of two parallel rows of cathodes and anodes, with a 10 ft
space between the rows. Within each row, the electrode spacing was
20 ft. The depth of embedment was 50 ft. Power was applied at
150 volts (0.5 volts/cm). A partial view of the installation, which
used railroad rails for anodes, is shown in Fig. 15.

     After several months of treatment, during 1977-78, the
excavation was successfully carried out with side slopes of 1 on
2.5, as shown in Fig. 16. Several feet of sand-gravel were placed
in the bottom of the cut and on the sideslopes, and the bottom
protection also included a layer of filter fabric. Although the

track through this cut is subjected to heavy railroad traffic,
I have heard of no problems with the stability of the cut.

Excavation for Revelstoke Dam (British Columbia). Construction
of this 500-ft high dam was started in 1979, on the Columbia River,
and is still in progress. The dam is 5,300 ft long, and consists
of concrete gravity and earthfill sections. The foundation
conditions include up to 200 ft of sensitive silt and clay, which
had to be excavated in order to ensure stability of the dam and
for construction of a cutoff. Analyses indicated that, with the
existing conditions, the excavation slopes could not be steeper
than 1 on 5. However, results of laboratory and field electro-
osmosis tests lead to the conclusion that slopes as steep as
1 on 2.5 could be used (3).

The electrodes were installed at spacings of 15 and 20 ft,
along benches left in the slope as the excavation progressed. A
view of the slope is shown in Fig. 17. The power was supplied at
160 volts (0.26 to 0.35 volts/cm). The increase in strength was
sufficiently rapid that only slight delays were required prior
to excavation of each successive bench. The excavation was completed
and backfilled without any signs of instability.

Big Pic River Bridge (Ontario, Canada). In 1959, electro-
osmosis was first used to increase the bearing capacity of steel
H-piles. The application was for the foundation of the Big Pic
River Bridge, which is part of the Trans-Canada Highway (11).
The subsurface conditions consisted of 10 to 20 ft of alluvial
deposits, underlain by 40 to 60 ft of soft to firm varved clay.
The clay in turn was underlain by more than 250 ft of silt and

silty fine sand, which was under artesian pressure. Test piles
driven into this deposit had lower load capacities than piles
extending only to the bottom of the varved clay deposit. Because
the shorter piles could not provide the required design load of
40 tons, and the designers did not wish to radically change the
foundation design at a late stage in the project, the proposal
was made to increase the capacity of the piles by using the piles
as anodes during electro-osmosis treatment. Laboratory and field
tests confirmed the validity of this suggestion.

    After driving 56-ft long H-piles for each pier, 70-ft long
cathodes were installed around the perimeter of the pile installation,
as shown in Fig. 18. The average distance between the piles and
the cathodes was about 23 ft. Power was provided at 70 to 120 volts,
by means of generators. The average current consumption per pile
amounted to only about 15 amps.

    After 4 weeks of treatment, the bearing capacity of the piles
had typically increased to 70 to 100 tons, which was approximately
2.5 to 3 times the capacity before treatment. Fig 19 shows the
results of before and after treatment load tests, for one of the
piles. A number of piles were blocked out of the pier footings,
for subsequent load testing to permit evaluation of the permanence
of the treatment. Piles tested up to 10 years after treatment
showed no significant loss in bearing capacity.

CONCLUSIONS

Electro-osmosis, when applied to fine-grained soils, is an effective method for increasing the strength. This increase is principally the result of tension produced in the pore water as the water content is reduced and menisci are formed, and is also partially due to bonding and cementation of the soil particles.

Electro-osmosis is also effective for control of seepage forces, which is highly beneficial for stabilizing slopes in fine-grained cohesionless soils.

For cohesive soils, electro-osmosis usually results in an increase in the plasticity index, especially near the anode. In combination with a reduction in the water content, the change in plasticity more quickly reduces the liquidity index, and thus more effectively increases the strength of the soil.

For most soils, with negatively-charged soil particles, the pore water moves from the anode toward the cathode. Therefore, the main benefits are near the anode, and the effects decrease toward the cathode. The strength near the cathode can also be increased if treatment is maintained for a sufficiently long period.

The conductivity and coefficient of electro-osmotic permeability decrease as the water content of the soil is decreased during treatment. The formation of an insulating zone around the anode and/or deposits at the cathode can also contribute to a reduction in these variables. The coefficient of electro-osmotic permeability may be 2 to 3 orders of magnitude greater than the hydraulic coefficient of permeability, which explains the relatively rapid benefits of electro-osmosis.

The pH of the discharge at the cathode will normally be
considerably higher than the pH of the pore water before electro-
osmosis treatment. The pH usually increases during the initial
stage of treatment, to highly basic values, and then decreases as
electro-osmosis becomes less effective. The alkalinity of the
pore water may result in some bonding and cementation of soil
particles, and thus enhance the benefits of electro-osmosis.

Numerous field applications for varied purposes have proven
the usefullness and long-term effectiveness of electro-osmosis
for solving difficult engineering problems. Because the effects
are still regarded with skepticism by many engineers, this method
is usually not considered for application until other more
conventional methods have been discarded as being either more
expensive or inadequate. However, this attitude appears to be
changing as more applications are successfully completed.

ACKNOWLEDGEMENTS

I gratefully acknowledge the contribution of Mr. R. W. Loughney,
of Loughney Dewatering, Inc., who was kind enough to provide me
with numerous photographs of some of the many electro-osmosis
projects successfully executed under his guidance. A large number
of these photographs were shown during the lecture on March 8, 1983,
but only several are included in this published version due to
space limitation. I also thank Mr. Loughney for reviewing a draft
of this paper. Special thanks are also given to my son Dirk, who
is a partner of Casagrande Consultants, for his assistance in
preparation of this paper.

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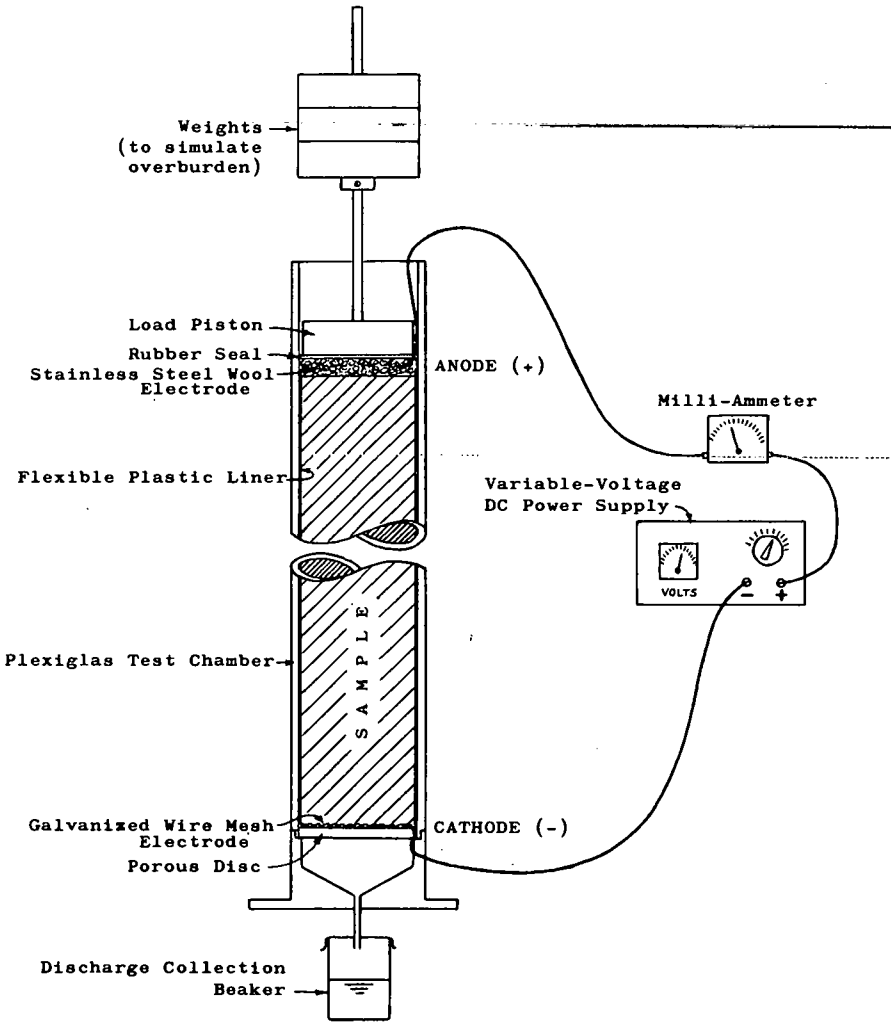
FIG. 1.   EXAMPLE OF LABORATORY ELECTRO-OSMOSIS TEST EQUIPMENT
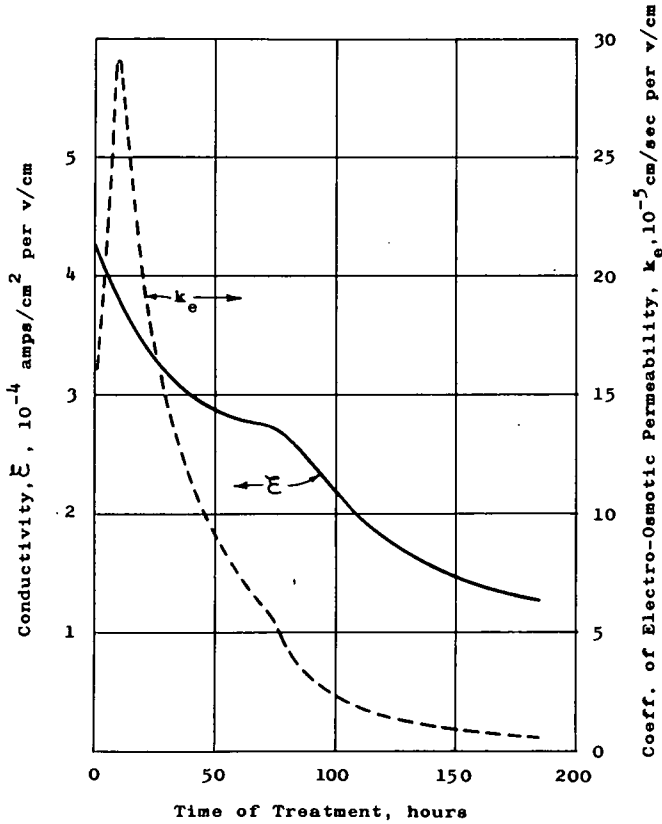
FIG. 2. CHANGE IN CONDUCTIVITY AND COEFFICIENT OF ELECTRO-
         OSMOTIC PERMEABILITY DURING TREATMENT OF SILTY CLAY
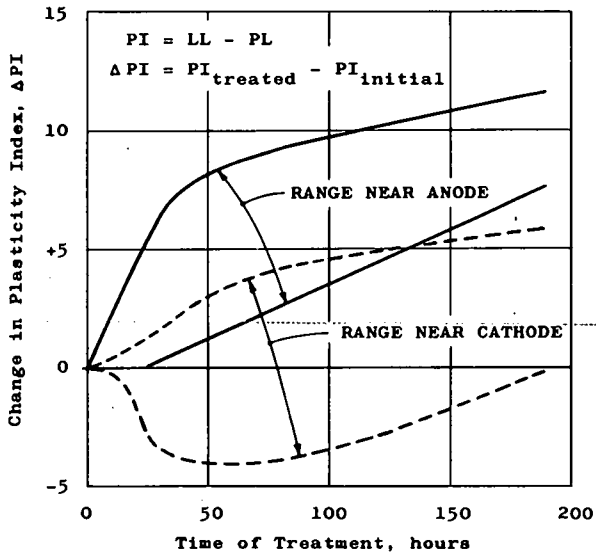
FIG. 3.   CHANGE IN PLASTICITY DURING TREATMENT OF
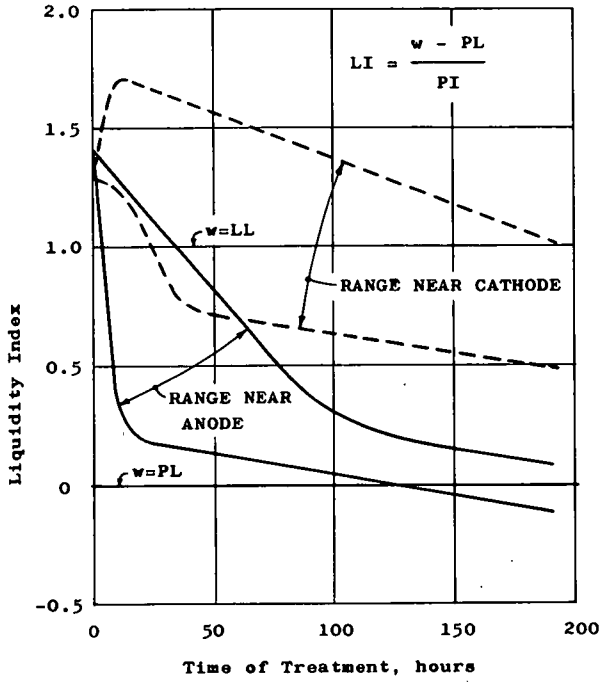   SILTY CLAY

FIG. 4.   CHANGE IN LIQUIDITY INDEX DURING
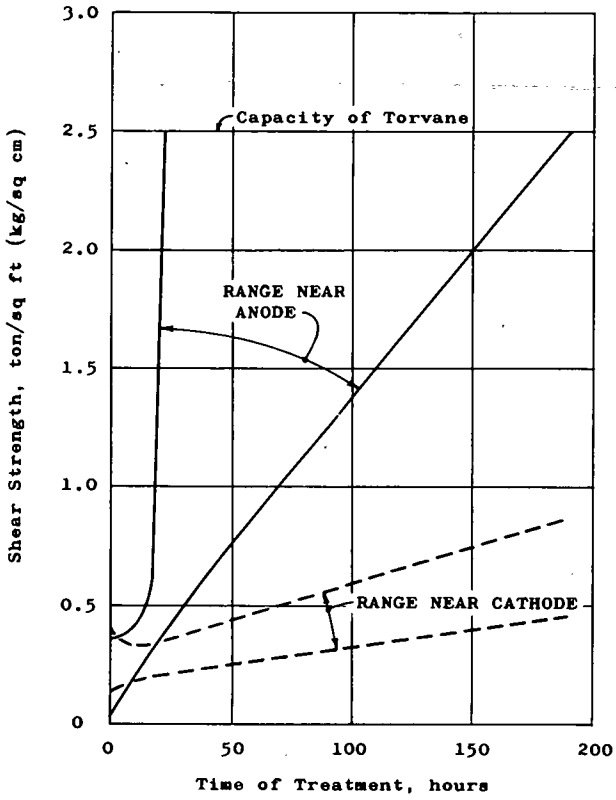   TREATMENT OF SILTY CLAY

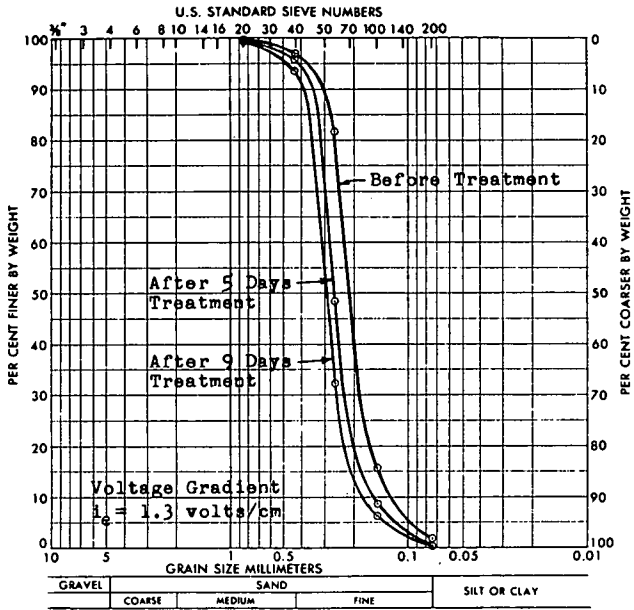FIG. 5.   CHANGE IN SHEAR STRENGTH DURING TREATMENT
           OF SILTY CLAY

FIG. 6.   CHANGE IN GRAIN SIZE DISTRIBUTION OF FINE
          QUARTZ SAND DUE TO BONDING OF PARTICLES
          DURING ELECTRO-OSMOSIS
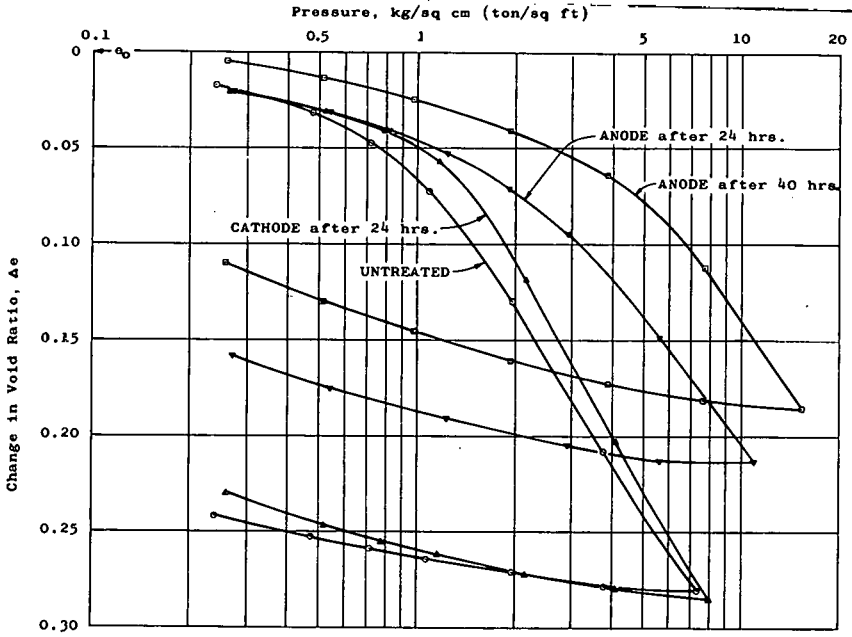
FIG. 7.   COMPARISON OF CONSOLIDATION CURVES FOR UNTREATED AND TREATED SILTY CLAY
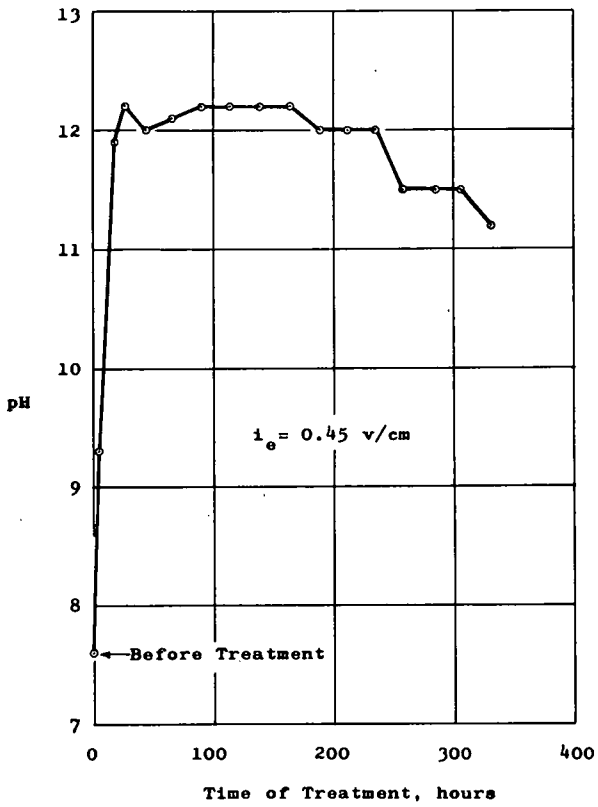
FIG. 8.   CHANGE IN pH OF DISCHARGE DURING
          TREATMENT OF SILTY CLAY
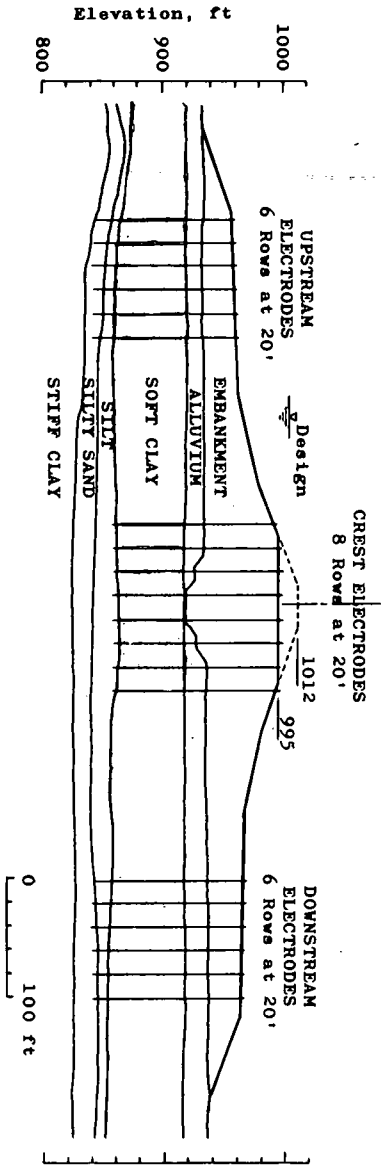
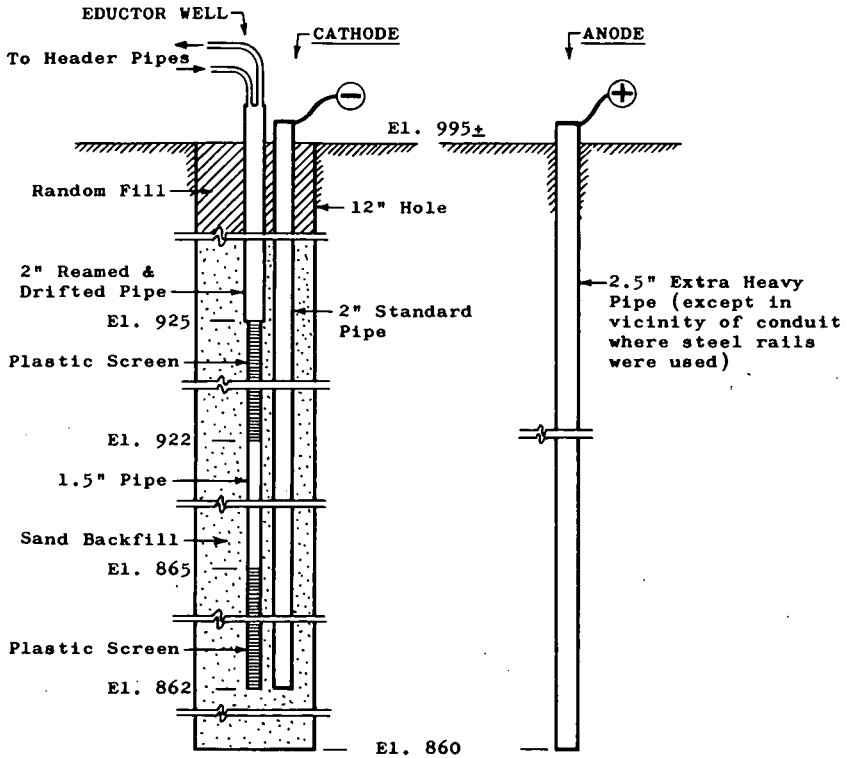FIG. 9. CROSS-SECTION OF WEST BRANCH DAM AND FOUNDATION, SHOWING LOCATIONS OF ELECTRODE ROWS

EDUCTOR WELL

To Header Pipes

CATHODE

ANODE

El. 995±

Random Fill

12" Hole

2" Reamed &
Drifted Pipe

El. 925

2" Standard
Pipe

2.5" Extra Heavy
Pipe (except in
vicinity of conduit
where steel rails
were used)

Plastic Screen

El. 922

1.5" Pipe

Sand Backfill

El. 865

Plastic Screen

El. 862

El. 860

FIG. 10.   DESIGN OF ELECTRODES ALONG CREST OF WEST BRANCH DAM
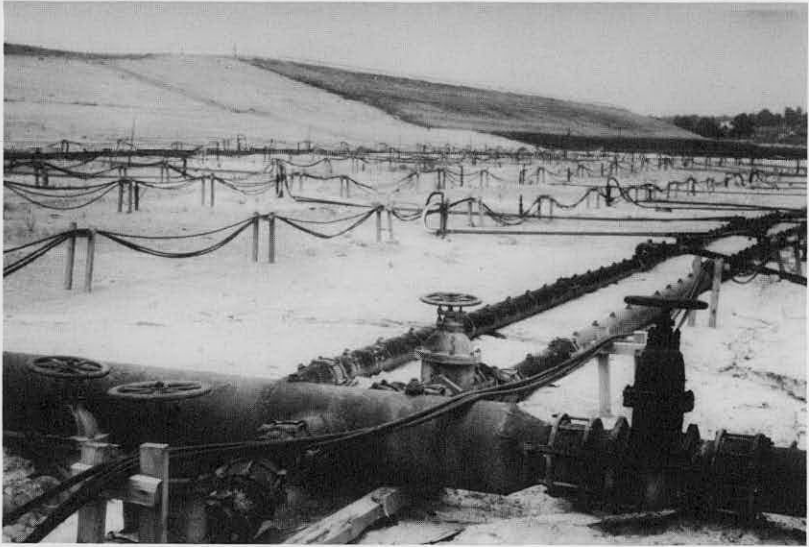
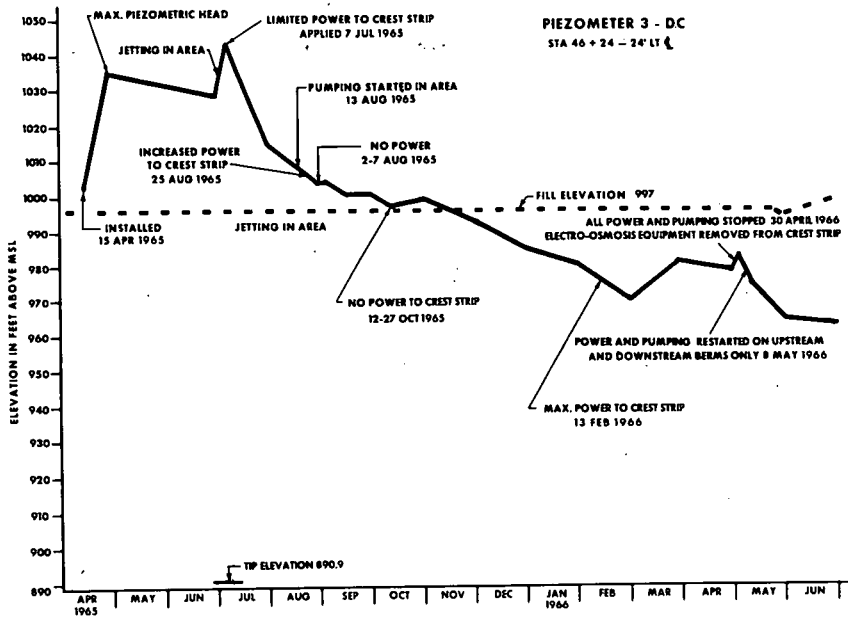FIG. 11.   VIEW OF ELECTRODE INSTALLATION ALONG DOWNSTREAM BERM OF
          WEST BRANCH DAM

FIG. 12.   EXAMPLE OF REDUCTION IN PIEZOMETRIC LEVEL IN CLAY STRATUM
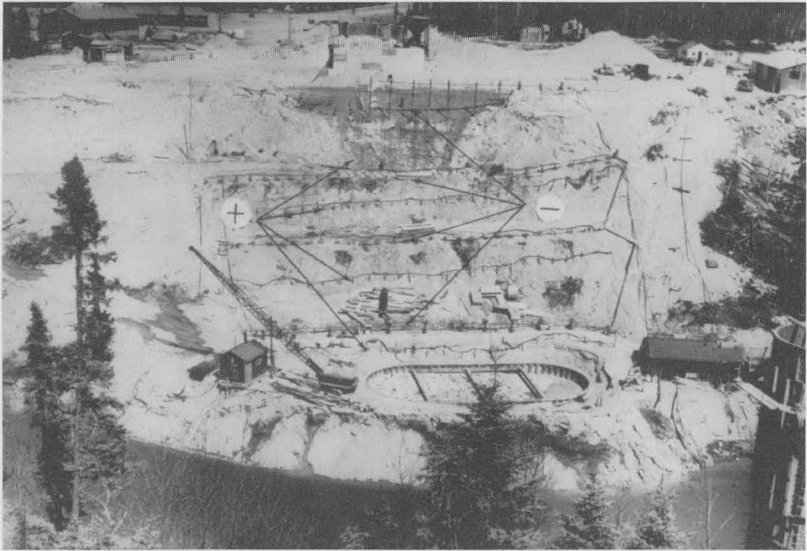   DURING ELECTRO-OSMOSIS TREATMENT AT WEST BRANCH DAM

FIG. 13.   GENERAL VIEW OF ELECTRODE INSTALLATION FOR EAST RIVERBANK
           PIER CONSTRUCTION, LITTLE PIC RIVER BRIDGE

FIG. 14.   ROW OF CATHODES PARTIALLY EXPOSED BY EXCAVATION OF STEEP
           SLOPE IN STABILIZED RIVERBANK, LITTLE PIC RIVER BRIDGE

FIG. 15.   ELECTRODES INSTALLED FOR CANADIAN PACIFIC RAILWAY CUT

FIG. 16.   POST–TREATMENT EXCAVATION AND BACKFILLING OF CUT FOR
          CANADIAN PACIFIC RAILWAY

FIG. 17.   200-FT HIGH EXCAVATION SLOPE IN STABILIZED SILT,
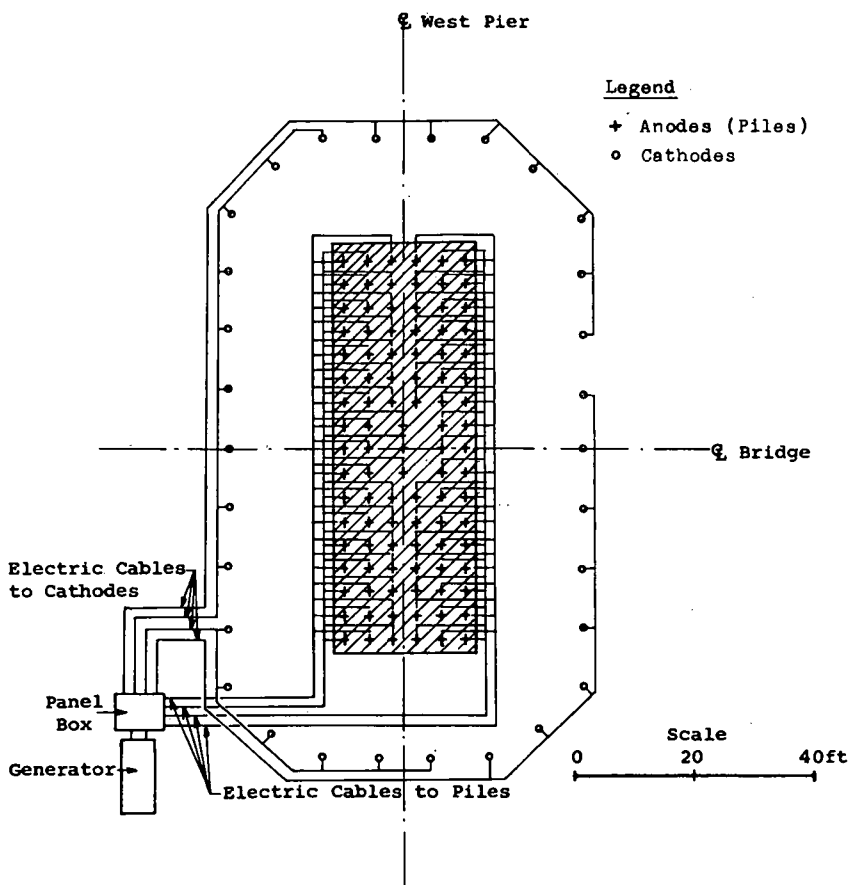   REVELSTOKE DAM

FIG. 18.   ELECTRODE INSTALLATION FOR TREATMENT OF PILE FOUNDATION, BIG PIC RIVER BRIDGE
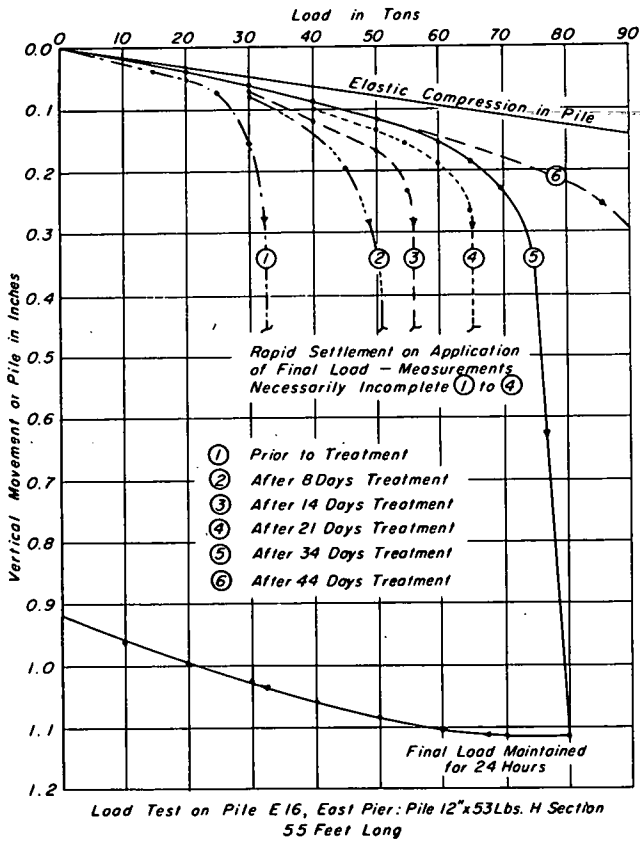
Load Test on Pile E16, East Pier: Pile 12"x53Lbs. H Section
55 Feet Long

FIG. 19.   RESULTS OF LOAD TESTS SHOWING INCREASE IN
CAPACITY OF ONE STEEL PILE DUE TO ELECTRO-
OSMÓSIS TREATMENT, BIG PIC RIVER BRIDGE