Screenings from the Soil Research Lab

IOWA ENGINEERING EXPERIMENT STATION
IOWA STATE UNIVERSITY of Science and Technology
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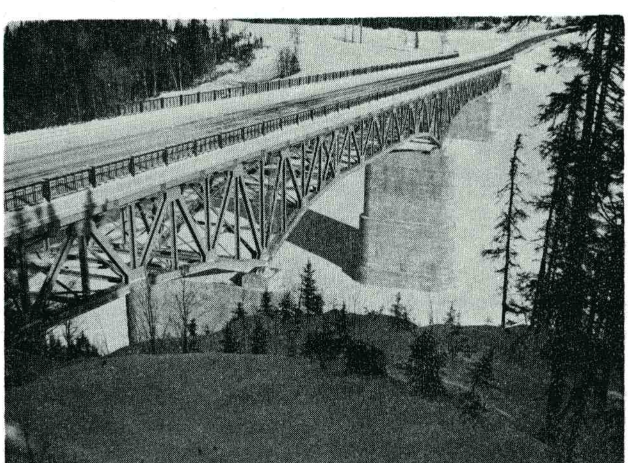
ELECTRICAL DRAINAGE OF SOILS

A Shocking Exposé; Watt's Watt Witt Watts

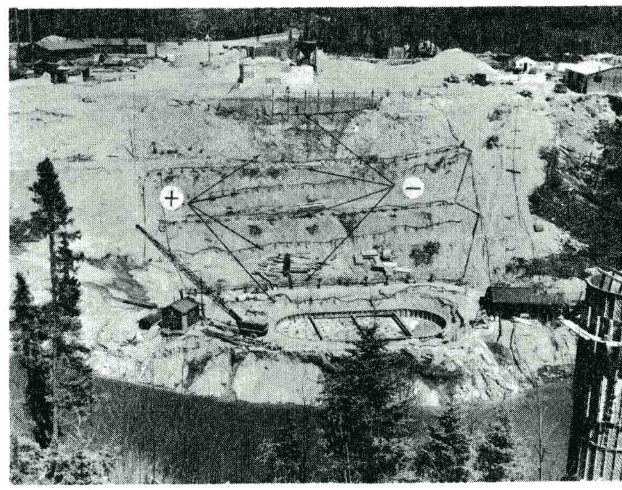
Un-man the pumps, lads, and dry away those tears, fears, ears and backsides. Step into the fo'c'sle and we'll narrate the greatest discovery since Grandpa's Electric Belt took the gastritis out of his dyspepsia and simultaneously sweetened his corns.

But we suffer the chore, for electrical gadgetry is so commonplace. So many things are electric, from clocks to can openers, frying pans to chairs. Suddenly the world has become a Leyden jar, lit up and running, ever in danger that a little mismanagement may set off a precipitous discharge. But we mustn't lose heart, mates; a Leyden jar does not hold its charge forever; demilitarization is largely a matter of forgetfulness.

The natural histories of water and electricity are intertwined like two dogs sniffing navels. For example, there was the incident of Dr. Franklin lofting his kite in a rainstorm and almost catching his death of sparks. An indirect but more useful connection is through the Cardinal Rule of Hydrology*; water over the dam is not merely water over the dam; it generates hydroelectric power.



Little Pic River Bridge on the Trans-Canada Highway, Marathon, Ontario.



Electrical stabilization of a silt soil to allow excavation for bridge piers. Oval area is the complete dation for one pier. Above this the bank is laced with rows of anodes (+) and cathode well points (-), all delivering a large charge. Electricity forces water out of too-wet soil. For a "before" picture illustrating need, turn the page. Completed bridge is shown below.

Electro-osmosis

The reverse of water over the dam is electricity which turns the pump that pumps the water, much to the distress of windmill salesmen. But our subject is nothing so prosaic, dull or efficient as pumps. Instead we will use only electrons, wires, and pipes--no pumps, lumps, or hidden devices; no sorcery, trickery, or calling on the occult; and only incidental use of prayer.

Purely electrical movement of water is not a mere laboratory curiosity; now it is a field curiosity as well. Electrical drainage will de-water and stabilize problem soils that refuse to be de-watered by ordinary means. That is, ordinary pumps can push water endless distances once they've got ahold of it, but a pump drawing from a well point can only muster so much suck. Fine silty and clayey soils are so tenacious the water won't run out by itself; it must be driven out or chased out with electrons. The action is termed electro-osmosis: Osmosis means diffusion of a fluid through a membrane; here soil is the membrane, and electricity is the driving force.

* Water runneth downhill.

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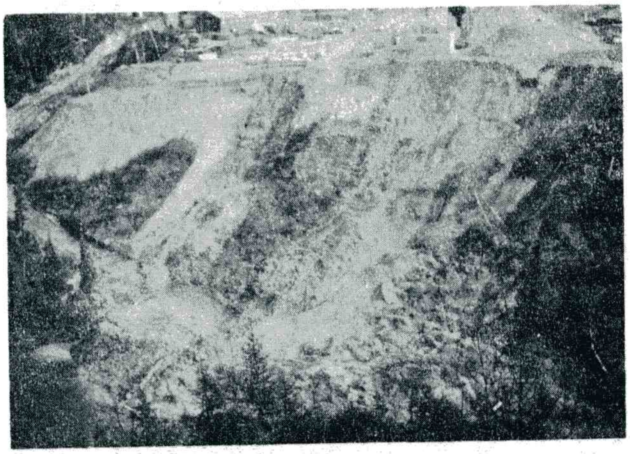


Slide. Soil as the Little Pic Bridge in Ontario averaged 26% water, and slides were set off at the merest drop of a pile driver. Reducing the moisture content 3% removed the danger.

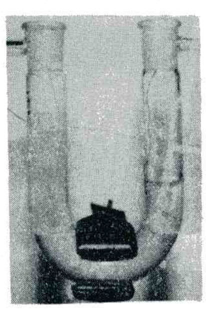
HYSTERICAL BACKGROUND

a. Discovery

In 1807 Ferdinand Reuss was puttering around in his garden in Moscow when it occurred to him to try a little electrolytic decomposition of water into the component H_2 and O. This was all the rage just then, having been discovered only a few years earlier. To be different, Reuss put two rods into the moist earth of his garden rather than into the usual glass of water.

It's beginning to look as if electro-osmosis might have been discovered by accident, but all Reuss saw was bubbles of gas--no water movement to or from the electrodes. Fortunately he became intrigued as to how the electricity could move through the ground so readily. He went to the lab.

Reuss reasoned that something in the water must have carried the "galvanic fluid," as they called electricity in those days. Therefore the water must move? To find out, Reuss put some powdered quartz in the bottom of a U-tube, filled it with water, and stuck an electrode in each side. The current was turned on, and the water level rose on the negative side. When the battery was disconnected, water levels again became level. Reuss could now retire to a life of mountain climbing and political comment. His name was made.



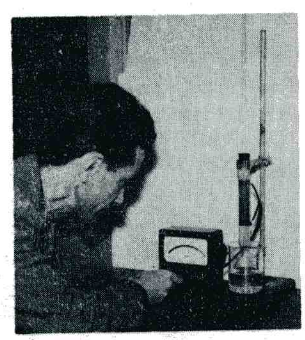
b. Elaboration

After a land is discovered, exploration continues until the area is fully mapped and in hand, i.e., taken from the Indians. In 1852 a German named Gustav Wiedemann slew a few when he discovered that the volume of water moved is proportional to electric current (amperes), and that water pressure built up by electro-osmosis is proportional to applied voltage. Followers were so elated they called these Wiedemann's first and second laws.

Wiedemann also found that certain salts or acids in the water could stop the flow, but this is sort of a negative result and not good material for a law.

Ingenious experiments were conducted a few years later by Georg Quincke. Although Georg was too late to discover any more empirical laws, he was very thoughtful about explaining things.

Quincke demonstrated that most materials have a negative surface charge which varies depending on the material, and nearby water is in effect charged positively. When an external voltage is applied, water moves to the negative pole. From this, Quincke reasoned that the converse also should be true; if water is mechanically pushed through capillaries it should make a voltage. This he called <u>streaming potential.</u>



Research Associate Turgut Demirel and apparatus. Water from the glass standpipe permeates downward through the soil, causing a voltage difference or streaming potential between the top and the bottom.

c. Formulation

In 1879 von Helmholtz worked from Quincke's model and published a famous bit of arithmetic which describes electro-osmotic flow through a rigid, straight capillary tube. This is known as the Helmholtz equation or sometimes the Helmholtz-Smoluchowski equation after Smoluchowski re-derived it showing that the capillaries can be crooked:

$$q_e = \frac{EDr^2\zeta}{4nL} , \qquad (1)$$

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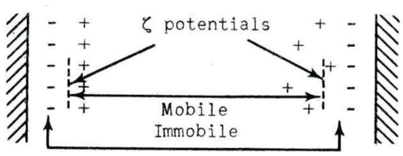
or, milliliters of water, q_e, equals voltage E, times dielectric constant D, times capillary radius squared, times zeta potential ζ, all divided by four times viscosity n, times length of the capillary L between electrodes. Ah, life has that old zip again!

The Double Layer

à la Quincke-Helmholtz   à la Gouy-Freundlich



Helmholtz assumed an ideal (+) and (-) double layer arrangement at the surfaces of capillaries, the +'s being like platoons of mercenaries ready to march anywhere on command. In 1910 Gouy suggested that they might be more like grasshoppers. Meanwhile Freundlich and Smoluchowski pointed out that zeta potential, or marching strength, is not all it should be; that perhaps the army has some lazy ones or deserters. Now the double layer is believed to be diffuse, with some (+) charges immobilized by attraction to the opposite sex, that old feminine negative.

Carrier pigeons

One final bit of theory--what are those positive charges, i.e., what moves? In a word what moves is ions. "Ion," from Greek, appropriately means "going." Ions are charged atoms such as hydrogen, sodium, calcium, etc. Positive ions are called cations (cat-ions) because they go to the cathode, which is negative. Conversely, anions go to the anode.

When cations go, they apparently drag along clusters of water molecules, explainable because water molecules have (+) and (-) ends on them and are attracted like chickens to corn.

Water molecule   Cation + water molecules

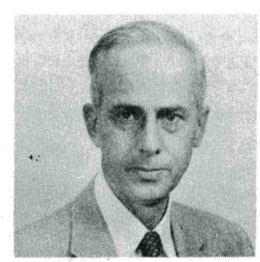
Since capillary walls are coated with hydrated ions on the move, free water in the capillary is also dragged along, greatly increasing the effectiveness of electro-osmosis.

BACK DOWN TO EARTH

Electro-osmosis finally made the full circle by 1930, when Leo Casagrande of Berlin (now of Cambridge, Massachusetts) studied electrical treatment of soils. He found that treatment, particularly utilizing aluminum anodes, caused permanent hardening and drying of soft, mucky soils.

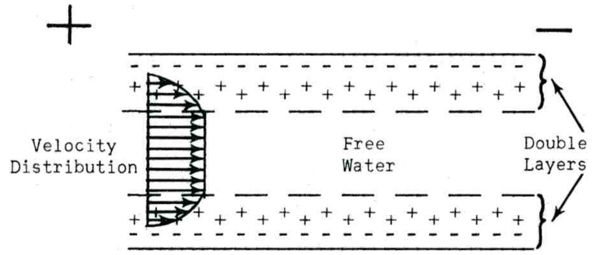
Beginning in 1939, Casagrande engineered a series of practical applications of electro-osmosis to firm up the heart and foundations of mighty Germany, or at least take some of the water out. The first application was at Salzgitter in northern Germany, at a railway cut which slid in as fast as the earth was removed.

Twenty well points spaced at 30 foot intervals, each sunk $22\frac{1}{2}$ feet into the embankment, drew practically no water by ordinary pumping. The well points were then made negative, half-inch pipes being driven between the well points and made positive to complete the circuit. A 180 volt potential was applied. Immediately the wells began flowing at the rate of 90 cubic feet per hour, or about $22\frac{1}{2}$ gallons per well per hour. By the next day the area was stabilized, and excavation was continued with no further difficulty. The total energy consumption was one kilowatt-hour per cubic yard of earth removed.



Leo Casagrande

Other applications in the 1940's were in excavations for bridges, tunnels, and trenches. These trials not only showed that electro-osmotic drainage of soils will work; in some situations it is highly practicable and the thing to do.



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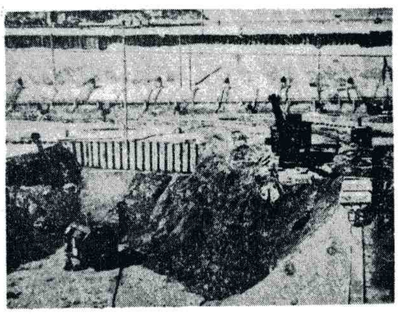
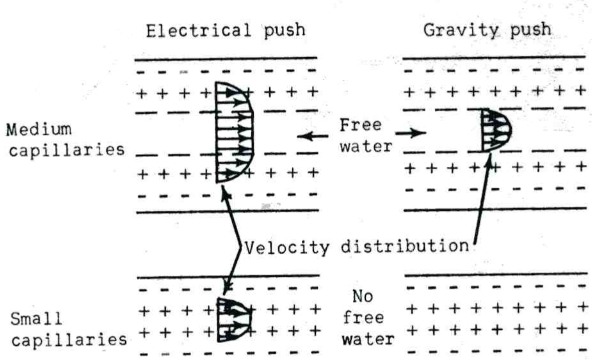
U-boat Pen

A dramatic application laden with nostalgia is stabilization of a U-boat pen at Drontjem, Norway. The walls of a proposed 46-foot excavation were protected by two rows of steel sheet piling, but as excavation proceeded, the sheet pile moved and the bottom of the excavation heaved up. Electrodes were driven at 15 foot spacing, alternately (+) and (-), to a depth of 60 feet. Forty volts was found to be sufficient push for the electricity, and within two days excavation was resumed with no further difficulty. Total power consumption, 0.4 kwh per cubic yard of earth removed.



ELECTRODES OR PUMPS?

Electro-osmosis finds its particular vocational niche with fine-grained soils where ordinary wells or vacuum wells won't work or are too slow; see below. Small capillaries contain more charges than a TV shop in a poor neighborhood, and as any mother knows, small charges can be hurried along electrically when gravity alone won't do the job. Often the driving forces are combined; electricity attracts and then pumping takes over.



Proof and permeability

Returning to the Helmholtz equation for water flow in a single capillary equation (p. 2), by assuming a few things constant and substituting capillary cross-sectional area for the radius squared ($a = \pi r^2$), we get

$$q_e = c_1 \, i_e \, a, \tag{2}$$

where i_e is the voltage gradient, E/L, and $c_1 = D\zeta/4\pi\eta$. For a bundle of capillaries such as in soil, the equation may be re-written

$$Q_e = k_e \, i_e \, A, \tag{3}$$

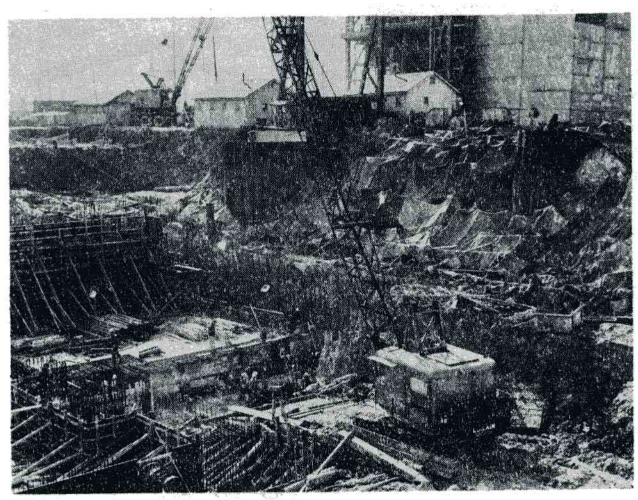
where A is the total pore area transverse to the direction of flow.

Here k_e is defined as the electro-osmotic coefficient of permeability, cm/second per volt/cm. If voltage gradient, i_e, is volts per cm and A is in cm^2, Q_e gives the water discharge in cm^3 per second.

The Good Lord smiles at him who fools with electricity; when zeta potential goes up, capillary size usually goes down, and electro-osmotic permeability does not vary much from soil to soil. A good average value is 0.5×10^{-4} cm/sec for 1 volt/cm. Extremes are 0.2 to 0.7.

In practice, permeability and flow rate often change as drainage continues, partly because of the change in availability of water molecules. Casagrande points out that flow practically ceases after a soil reaches the plastic limit. Actually, forever and amen, that's dry enough.

Another very important factor affecting flow rate is identity of the carrier ions. Some ions transport water better than others, just as some dogs have more fleas. Work by Dr.



Excavation at the Joppa, Illinois, power plant. The cut was protected by sheet pile but as digging continued the clay bank on the right started to move in, letting the building down (upper right) and painfully shearing off its piles. Electrical drainage increased shearing strength five times and effected a cure. Anodes and cathodes may be seen poking up under the tarps.

Ralph Rollins in this laboratory showed aluminum to be very flea bitten, and transporting ability of this and other ions in a kaolin clay was in the order Al > Na > Ca > Fe > H. Electro-osmotic flow often slows down after metallic ions complete their journey and are depleted, leaving only water-derived hydrogen as the substitute stevedor. In calcareous soils, calcium moving to the cathode is deposited as hydrated lime, $Ca(OH)_2$, retarding flow.

Finally there is the effect of consolidation, mentioned later. When a clay consolidates the pores become smaller, and electro-osmotic permeability reasonably should fall off. Theoretically k_e is related to what engineers call the void ratio, being proportional to $e/(1 + e)$.

The way of Poiseuille (Pwa-zaiy)

An interesting contrast to electro-osmosis is Poiseuille's equation for hydraulic flow in a capillary:

$$Q_h = k_h\, i_h\, A. \qquad (4)$$

Note the analogy with equation (3). However, whereas k_e varies perhaps two or threefold, the hydraulic coefficient of permeability, k_h, varies in the extreme. Usually it is in the neighborhood of 10^{-2} to 10^{-11} cm per second, depending on whether the soil is a sand, silt, or clay, and that is a rather large neighborhood. In other words, ordinary wells won't drain an impermeable clay, which is what we've said before.

Example: If k_h of a clay is 10^{-7} cm/sec, what hydraulic gradient would effect the same drainage as a potential gradient of 0.10 volt/cm?

Ans.

$$Q_e = 0.5(10)^{-4}\ \frac{\text{cm/sec}}{\text{volt/cm}} \times 0.10\ \text{volt/cm} \times A\ \text{cm}^2$$

$$= 0.5(10)^{-5}\ A\ \text{cm}^3/\text{sec}.$$

$$\text{If } Q_h = Q_e,\ 0.5(10)^{-5}\ A = 10^{-7}\ i_h\ A$$

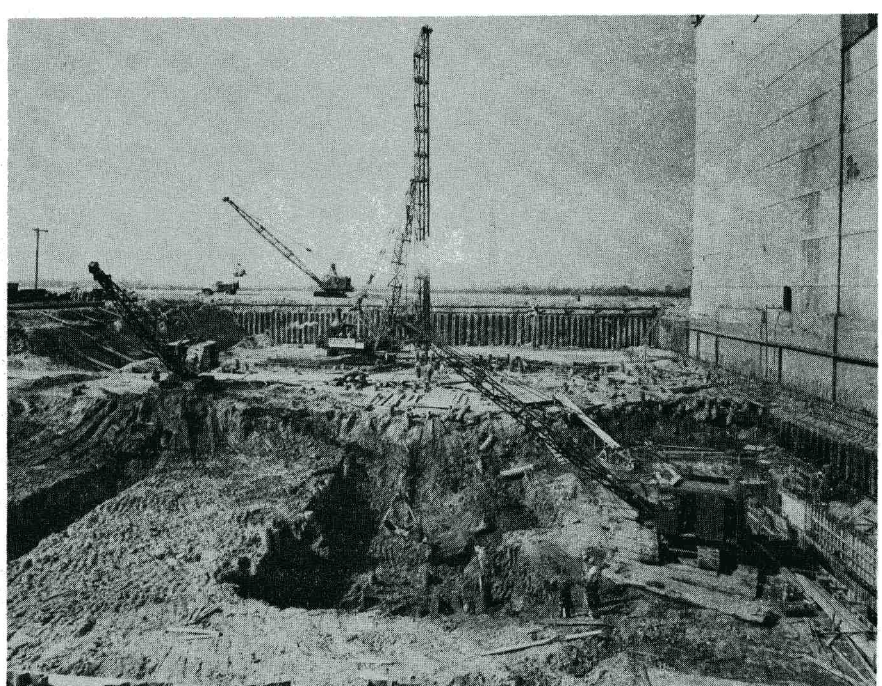
$$i_h = 50\ \text{cm/cm or } 50\ \text{ft/ft}.$$

Since the maximum suction is limited by atmospheric pressure to about 27 feet of water, wells for equivalent drainage would have to be spaced about half a foot apart. We'll use electricity.

PRACTICAL PRACTICE

This may seem a horrendous bit of mathematics except to engineers, who read an equation like Ma reads the recipes on the backs of frozen pies. But we fear the public eyeballs may be a bit glassy--perhaps it will relieve the vitrification to spin a joke or two:

When rockets fall
And singe us all
And the world is filled with groaning,
Please don't revile;
Project thy smile,
"Good moaning, friends; good moaning."



Power plant excavation at Bay City, Michigan. The upper 20 feet of strata are sandy, and were de-watered with conventional and vacuum well points spaced 20 feet apart around the perimeter. Then deeper excavation into silt caused shifting of the sheet pile in the foreground.

The well points were converted to cathodes by driving pipes between them and hooking up the generators; after 3 or 4 days de-watering was sufficient that excavation could be continued. Note the river perched almost at ground level in the background.

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Generators

Electro-osmosis requires current to be strictly one way, or the water won't know which way to turn. D.C. generators putting out from 30 to 180 volts have been used--in fact, ordinary welding units can turn the trick. Voltage divided by distance between electrodes is i_e of equation (3) and thus is proportional to rate of water flow. However, i_e should not exceed about a volt per inch or appreciable wattage will be lost for useless heat. Also, higher voltage means more current.

Current

So far the equations have kept judiciously mum on electrical current requirements. For this we pull in the first three years of undergraduate electrical engineering: $I = E/R$ (Ohm's Law). Or to put it another way, $I = E\sigma$, where I is current in amperes, E is in volts, and σ is mhos*. Conductivity of soils in mho/cm may be measured as the number of amps through a square centimeter when the voltage gradient, i_e, is 1 volt/cm. Conductivities in saturated soils vary from about 75×10^{-4} for sodium montmorillonite to 10 to 20×10^{-4} for friable silt.

Amperage requirements are loosely predictable from conductivity, voltage, and electrode geometry. Solving equations for the latter may be a little wierd, so a model may be used. Pins stuck through cardboard represent the electrodes; a tray of salt water represents the soil.

Aluminum anodes

As previously indicated, some of the earliest work on electro-osmosis in soils utilized aluminum anodes, in recognition that carrier ions move along and can be replaced. Therefore one might as well add something dynamic like aluminum.

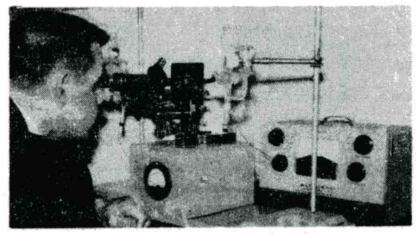
Aluminum ions do well at holding clay together, and aluminum hydroxide cements the soil. Experiments by Prof. M. G. Spangler and others showed the method could be used to greatly increase bearing values of aluminum pile. However, it has not been extensively employed in practice. Too sedentary; much easier for an engineer to keep driving until he can "feel" the pile take hold.

Consolidations and sheer strength

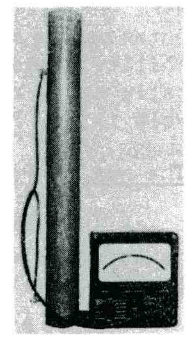
There is still some hocus-pocus concerning strength gains of soils during electro-osmosis. Unusually high and rapid consolidations and strength gains are observed, particularly if the soil is already under load.

One explanation is that pore water is under tension when the electrons are chasing, and the tension helps collapse the walls of the capillary. Under ordinary conditions electro-osmosis is equivalent to increasing the consolidating load 0.01 to 1.0 tons per square foot.

* Ohm spelled backwards. Some sciences use pig Latin.



Capt. Don Senich, a graduate student in soil engineering, finds zeta potential of clay particles by watching them move in an electric field. The phenomenon is called electrophoresis, similar to electro-osmosis except that clay particles are not held rigidly as capillaries, but are suspended and free to move. In electro-osmosis the clay can't move so the water moves instead.



On the right is illustrated the converse of electrophoresis, called sedimentation potential. Voltage gradient, top to bottom, results from charged clay particles settling in water.

ACKNOWLEDGMENTS AND REFERENCES

For more about the wet electrons see "Review of Past and Current Work on Electro-osmotic Stabilization of Soils" by L. Casagrande, Harvard Soil Mechanics Series No. 45, revised 1957, See also "Electro-osmotic stabilization of soils," Jour. Boston Soc. Civil Eng., Vol. 39, 1952. Work of Rollins is published in Highway Research Board Proc. V. 35, 1956.

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On-the-job photographs in this issue are courtesy of the Wellpoint Dewatering Corporation, 881 East 141 Street, New York 54, N. Y.

W E A R E S A D

TO REPORT a major error in the last issue. The soil textural triangles, p. 6, were reversed: "New" is really old, and "Old" is new. There is no excuse for this, and you will be pleased to know the Editor promptly shot himself close between the toes. Please make the change if you save "Screenings."

RLH

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