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A STUDY OF SENSITIVITY IN LEDA CLAY

BY

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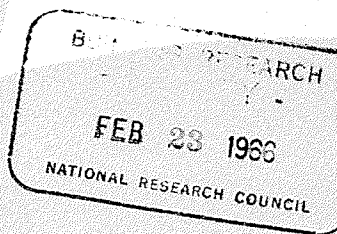
ETUDE DE LA SENSIBILITE DE L'ARGILE LEDA

SOMMAIRE

La teneur en sel de l'eau interstitielle a relativement peu d'influence sur la sensibilité de l'argile Leda que l'on trouve dans la région d'Ottawa. Les valeurs de sensibilité peuvent varier de 10 à 1000 pour une teneur en sel peu élevée (< 2g/litre). Quand la teneur en sel est plus considérable, les violentes réactions de floculation de l'électrolyte limitent la sensibilité, mais on a toutefois mesuré des valeurs atteignant 75. Le rapport établi expérimentalement entre le potentiel électrocinétique et la sensibilité s'accorde avec la théorie d'attraction et de répulsion des particules entre elles. Les principaux écarts sont imputables aux différences de diamètre des grains. Des analyses chimiques de l'eau interstitielle ont montré que les variations de sensibilité importantes, dans le cas d'une faible teneur en sel et particulièrement à l'intérieur d'un même profil, sont liées à la nature de l'électrolyte de l'eau interstitielle. Les sols exceptionnellement sensibles contiennent une quantité considérable de cations monovalents. Ce fait peut expliquer les variations importantes de sensibilité, mais on ne connaît pas encore la cause des faibles variations. L'auteur décrit en détail la technique de l'osmose électrique utilisée pour déterminer les potentiels électrocinétiques. On a également employé cette technique pour confirmer la théorie de Rosenqvist en ce qui concerne la sensibilité des sols que l'on sait être d'origine marine.

A STUDY OF SENSITIVITY IN LEDA CLAY[1]

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ABSTRACT

The sensitivity of Leda clay from the Ottawa area is relatively independent of the salt content in the pore water. Sensitivity values may vary between 10 and 1 000 in the low salt content range (less than 2 g/liter); at higher salt contents strong flocculating effects of the electrolyte limit the sensitivity, but values as high as 75 have been measured.

A relationship has been determined experimentally between electrokinetic potential and sensitivity that is consistent with the theory of interparticle repulsion and attraction. The main deviations are attributable to differences in grain size.

Chemical analyses of pore water show that large variations in sensitivity, particularly within one profile, are related to the nature of the pore water electrolyte in the low salt content range. Soils that are unusually sensitive have a high monovalent cation content. Large differences in sensitivity can be accounted for in this way, but the reason for small variations is still obscure.

The electroosmosis technique used to determine electrokinetic potentials is discussed in detail. This apparatus was used also to verify Rosenqvist's leaching theory of sensitivity for soils known to have had a marine origin.

INTRODUCTION

The unusual behavior of the fine-grained sedimentary deposits of the St. Lawrence Lowlands region of Eastern Canada is known to result largely from the highly sensitive nature of the soil. Sensitivity is the ratio of the natural shear strength of a soil to its remolded strength. Although Terzaghi (1944) defined it originally in terms of unconfined compressive strength, other testing methods have since been adopted for highly sensitive clays.

Numerous landslides of the flow type have occurred throughout the region, leaving characteristic landscars, some dating back into geological history. Generally, the identification of potential flow areas has been based on stability studies of recent slides. In some cases loss of stability has been definitely associated with external causes; some have been man made, and others have resulted from such natural causes as erosion. The suggestion has been advanced that in other cases changes within the material may have been responsible. It is not surprising therefore that considerable effort is being devoted to physico-chemical studies of this type of soil both in Canada and abroad.

Although there is an urgent need for a reliable means of predicting and controlling potential flow slides, the problem goes much beyond this because it affects all soil engineering problems. In extreme cases, undisturbed sampling and the preparation of samples for laboratory testing may be virtually impossible. Even with the greatest care the sample is partially remolded, and in extreme cases is transformed into a viscous fluid.

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Extensive investigations of the behavior of clay–electrolyte–water systems were undertaken, in conjunction with engineering tests, on similar deposits in Norway (Rosenqvist 1955). This led to detailed studies of the "leaching theory" of sensitive marine clays. In recent years there has been a much greater tendency to make use of the colloidal properties of soil and to apply them to engineering. Work on soil structure by Lambe (1953) and the theoretical and experimental study of swelling pressures in clays by Warkentin et al. (1957, 1958) are examples of the usefulness of this approach.

The electrokinetic behavior of sensitive clays, which forms the basis of this paper, has received little attention in the literature, although many of the physical manifestations of such systems are a direct result of the electrical properties of clay particles. The charged, diffuse double layer, which gives rise to electrokinetic phenomena and is also the basis for the present concepts of interparticle repulsion, does not appear to have been studied in connection with problems of sensitivity. In spite of the lack of experimental results the double-layer theory and the resultant interparticle repulsion have been specifically invoked in the explanation of (1) the structural arrangement of these soils during sedimentation, (2) *in situ* strength changes, and (3) fluid properties in the remolded state.

ORIGIN AND GENERAL CHARACTERISTICS OF LEDA CLAY

According to the geological studies of Sir William Dawson, as summarized by Johnston (1917) these deposits were thought to be marine sediments of the Champlain Sea, but the possibility that they are not uniquely marine in origin appears to have been suggested in the literature from time to time. One point of disagreement concerns the sequence of events beginning with the general uplift of the area and the recession of the sea. The probability of an extensive freshwater phase is strengthened by a recent report by Gadd (1963) stating that "a sudden influx of fresh water produced either by release of melt-water from glacial sources or, more likely, by the sudden release of large volumes of silt-laden water from the Great Lake region" was capable of considerable erosion of the old Champlain sediments, and subsequently resulted in a freshwater lacustrine or fluvial environment of deposition to which the origin of the upper (and younger) deposits is now assigned.

The Leda clays in the Ottawa–Hull area are sensitive to varying degrees and usually have a low salt content. If a freshwater phase is represented, the property of sensitivity must have been acquired by means other than *in situ* leaching. This aspect is, however, of passing interest in the present context. In the Ottawa–Hull area the salt content of the pore water is generally less than 2 g/liter, except at one sampling location where the salt increased from the surface and reached about 15 g/liter at 107 ft.

In general it may be said that there is no correlation between salt concentration and sensitivity such as has been reported for Norwegian soils. Leda clay is "inactive" and its mineralogical nature is similar to Norwegian sensitive clays, but, in general, the clay size fraction is higher, although a wide variation exists.

ELECTROKINETIC THEORY WITH PARTICULAR
REFERENCE TO CLAY–WATER SYSTEMS

When clay particles and water are brought into contact there is a spontaneous separation of charges at the interface that gives rise to electrokinetic phenomena. Lattice imperfections within the crystal account for the excess negative surface charge on clays. As internal compensation is not possible, the charge is balanced by positive ions in the surrounding liquid.

The concept of a fixed negative charge for clays and electroneutrality by cation adsorption is accepted generally, but the spacial distribution of cations is dependent on the properties of the solution. The salient features of one diffuse-double layer concept are diagrammatically depicted by Alexander and Johnson (1949) and are shown in Fig. 1. It incorporates Stern's model of a fixed
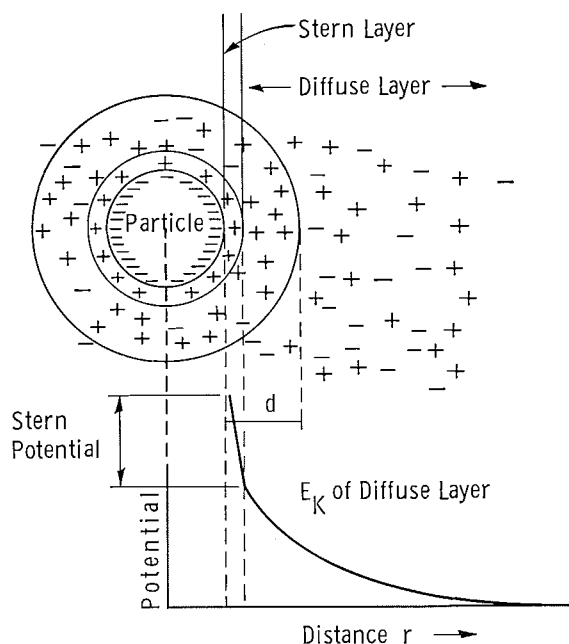
FIG. 1.   The electrokinetic potential E_k and the electrical double layer.

positive layer next to the surface through which the potential drops linearly with distance. The difference between the surface potential and the potential at the outer limit of the fixed layer is called the Stern potential. Beyond the Stern fixed layer is the diffuse layer, which is similar to the Gouy model through which the potential drops almost exponentially with distance.

When an external electrical potential is applied tangentially to the surface of the particle, the positively charged diffuse layer will be attracted toward the negative electrode (cathode), dragging the water with it. The negatively charged particle, along with an adsorbed layer of water called the immobile

layer, will be attracted to the positive electrode (anode). The potential difference between the slipping plane and that of the bulk liquid is known as the electrokinetic potential. As the electrolyte concentration of the solution is increased in clay–water systems there will be less repulsion between the charged particles. Particles will come closer together for two reasons: because the surface potential is reduced and the diffuse layer is compressed. Although electrokinetic potentials provide no information on interparticle attractive forces and the position of the slipping plane can be rather poorly defined, the magnitude of the potential can be used as a semiquantitative guide to the degree of repulsion.

Electrokinetic potentials may be measured in a number of ways.

(1) *Electroosmosis*: involving the movement of a liquid relative to the solid by the external application of an electrical field.

(2) *Electrophoresis*: involving the movement of a solid phase with respect to the liquid by the external application of an electrical field.

(3) *Streaming potential*: involving the movement of the liquid by mechanical means with respect to the solid, which gives rise to the electrokinetic potential.

(4) *Sedimentation potential* (Dorn effect): involving the movement of the solid by mechanical means (usually gravitational), which gives rise to the electrokinetic potential.

As electroosmosis was selected for this study, further comments will be confined to this technique. In the experiment, a liquid-saturated plug of solid particles is held in a fixed position, an external electrical potential is applied across the plug, and the liquid flow rate is measured. From measurements of osmotic flow, electrical current, and the specific conductivity of the pore water, the electrokinetic potential E_k may be calculated. The classical Smoluchowski–Helmholtz equation (Kruyt 1952) is

$$(1) \qquad\qquad E_k = 4\pi n v \lambda_p / \epsilon i$$

where n and ϵ are the viscosity and the dielectric constants of the diffuse layer respectively,

λ_p is the specific conductivity of the pore fluid,

v is the osmotic flow,

and i is the current.

Values of i and λ_p are in c.g.s. electrostatic units, since λ_p is usually in ohm^{-1} cm^{-1} it must be multiplied by 9×10^{11}, and i in amperes must be divided by 0.33×10^{-9}. The computed electrokinetic potential E_k is now in electrostatic units and must be multiplied by 300 to convert it to practical units of volts.

It may be pointed out that it was imperative to use electroosmosis because it was sometimes of special interest to retain the clay in its natural structure in the environment of its natural pore water. It was realized that with systems of small particles the electrophoresis method has many advantages if a dilute solution can be made of the clay–water system, but removal of the soil particles from their natural pore water environment would unquestionably change their electrokinetic characteristics.
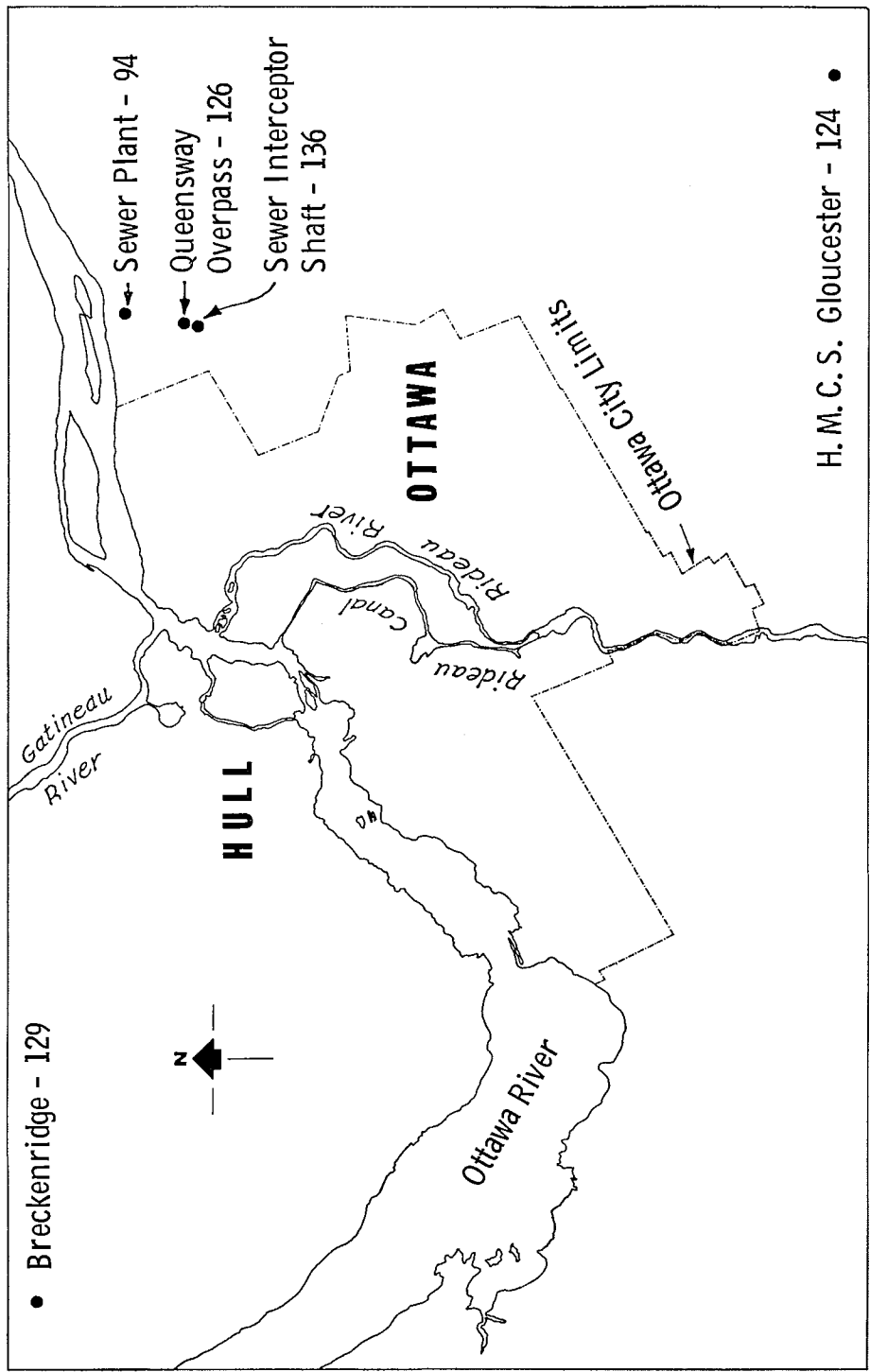
FIG. 2. Location of sampling sites in the Ottawa–Hull area.

As with other methods of determining electrokinetic potentials, there are limitations with the electroosmotic technique apart from uncertainties introduced by estimating viscosity and dielectric constant in the diffuse layers. The more important limitations are discussed in some detail by Kruyt (1952) and may be summarized as follows.

(1) Surface conductivity should not contribute significantly to the total conductance; a partial correction for this is possible.

(2) The radius of the pores must be many times larger than the thickness of the double layer.

(3) The flow of liquid must be laminar; this condition is usually easy to satisfy.

The reduction or correction of these uncertainties in the present study will be presented in detail in the discussion on measurement procedure.

MATERIALS

Most of the study samples were from the so-called "marine" deposits of the Ottawa–Hull area. Some were undisturbed samples obtained from blocks of soil taken from deep excavations. Others were obtained with the Norwegian thin-wall sampler or the Swedish foil sampler. Figure 2 gives a map of the area showing sample locations. Another soil included in the study was from Toulnustouc, Que., the site of a recent landslide near the St. Lawrence River.

The mineralogy of the Ottawa–Hull soils may be summarized as follows, based largely on the work of Brydon and Patry (1961).

(1) Montmorillonite or other expanding layer silicates are absent or present only in small quantities.

(2) Some chlorites and vermiculite are usually present.

(3) Illite, hydrous mica, and mica are the predominant clay minerals.

(4) Rock-forming minerals consisting of varying proportions of feldspars, quartz, and amphibole make up a large part of the clay-size fraction, with feldspars predominating.

(5) The same rock-forming minerals found in the clay are represented in the silt- and sand-size fractions.

(6) The major change accompanying particle size is an increase of phyllosilicates in the small-size fractions, with consequent dilution of the other minerals.

EXPERIMENTAL

Apparatus and Materials

An apparatus (Figs. 3 and 4) was designed for determination of the electrokinetic potentials based on electroosmotic techniques used by Douglas and Walker (1950), Goring and Mason (1950), Oakes and Burcik (1956). Alternating-current resistance measurements were made on the plug before and after electroosmosis measurements by an inner set of electrodes of the same

FIG. 3.   Assembled electroosmosis apparatus: (1) etched mirror scale.
FIG. 4.   Component parts of the electroosmosis apparatus: (2) inner electrode; (3) outer electrode; (4) calibrated capillary tube; (5) solution compartment; (6) sample holder; (7) filling tube.

FIG. 3

FIG. 4
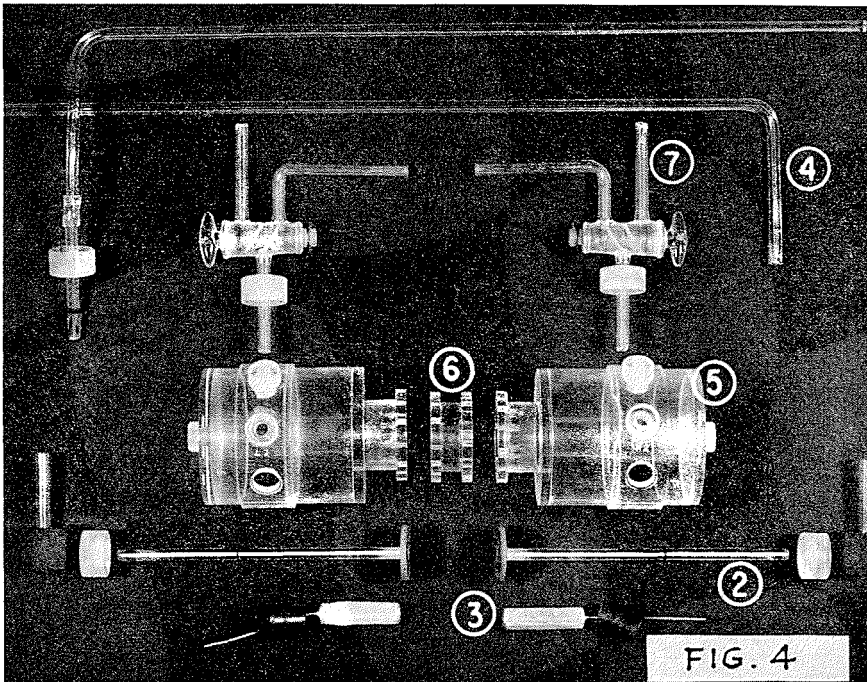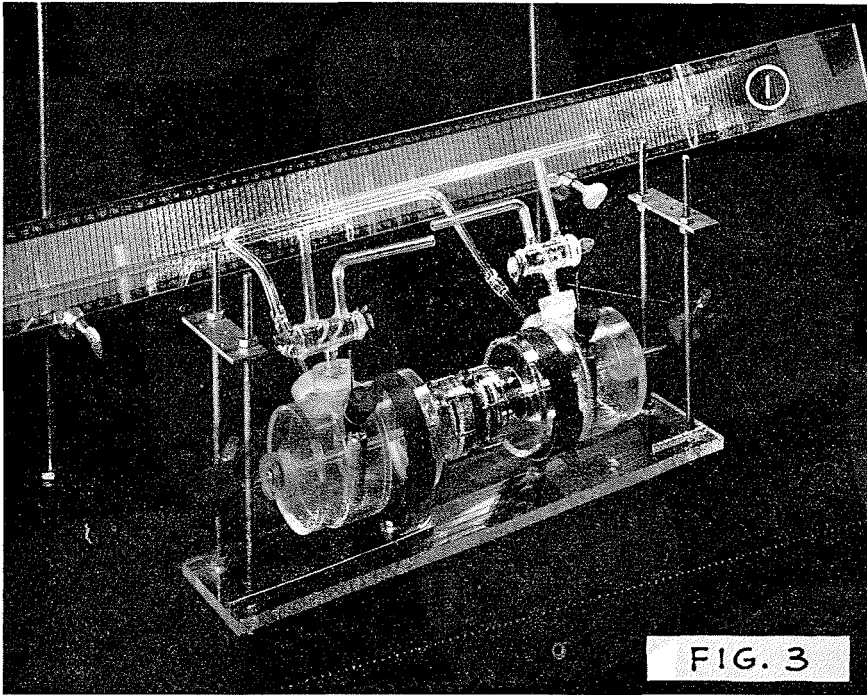
cross section as the plug. The center section containing the soil plug was designed so that undisturbed clay specimens could be pressed into the holder with a perfect fit between the holder wall and the specimen, in much the same manner as is used in the preparation of specimens for consolidation tests. For semifluid remolded soils the sample was retained between two coarse filter papers held in place in the sample holder by lucite retaining rings.

The inner electrodes consisted of coarse platinum gauze (covered with platinum black) held tightly against the soil plug by porous stones mounted on the ends of capillary tubes. Platinum lead wires were brought outside the cell through holes in the capillary tubes. Tests were done with and without the filter paper and showed no impedance to flow.

The potentials were imposed with the outer electrodes made of platinum gauze tubes. A layer of silver was deposited on the surfaces of the electrodes by electrolysis and they were subsequently chlorodized in a 0.1 N hydrochloric acid solution using an inert cathode. The outer electrodes were sufficiently removed from the soil plug to minimize the possibility of contamination of the plug.

The entire assembly was submerged in a constant-temperature bath at 25 ± 0.1 °C. The osmotic flow was measured on both the intake and outflow sides with calibrated capillary tubes mounted on a mirror containing an etched millimeter scale. The potential was applied in one direction for 10 min and then reversed for an equivalent period. Values were averaged for calculation of electrokinetic potential.

The electrical current through the system was continuously monitored by measuring the potential drop across a thermostated standard resistor in the circuit. It was held constant with a manually operated rheostat. The induced voltage drop was approximately 0.5 volt/in. of sample, and the osmotic flow varied between 0.2 and 0.05 cc for a 10 min period, depending on the plug material. The concentration of the solution in the compartments containing the outer electrodes was based on the predetermined specific conductivity of the pore water electrolyte of each sample, but it was not practicable to simulate the complex nature of the electrolyte.

The salt concentration of the pore water of soils was determined from the sample immediately adjacent to the sample plug. Extractions were carried out with a miniature pressure membrane apparatus. The resistance of the porous plug was measured in the cell between the inner electrodes with a 62/1 000 c.p.s. conductivity bridge after the apparatus was in thermal equilibrium with the bath. The conductivity of the extracted pore water was also measured with this instrument. Strength tests for sensitivity calculations were done according to the Swedish cone method (Hansbo 1957).

CORRECTIONS AND LIMITATIONS OF THE ELECTROOSMOTIC TECHNIQUE

If the specific conductivity of the bulk pore water is used to calculate the electrokinetic potential the results may be low for dilute solutions of the pore

water. As a consequence, *in situ* specific conductivity of the pore water was determined as follows (Briggs 1928). The resistance, R_p, of the plug containing the natural pore water was measured in the cell. After completion of the run the sample was remolded with sufficient dry salt to increase the salt concentration to more than 0.1 *N*. The new resistance of the plug (R_{KCl}) was then established, the concentrated solution extracted from the sample, and its specific conductivity λ_{KCl} established. Assuming the conductance capacity of the plug to be a constant, that is

$$R_p \lambda_p = R_{KCl} \lambda_{KCl},$$

then the value for λ_p, the specific conductivity of the *in situ* pore fluid, could be calculated. This value for λ_p was then used in equation (1).

A second limitation, which may reduce the calculated value for electrokinetic potential, occurs when the pore radius and the thickness of the double layer are of the same order. Bull (1905) showed experimentally that the potentials in glass capillaries are too low when the pore radius is less than 15 times the thickness of the double layer. Exploratory computations estimating the ionic strength of the pore water and the radius of the pores in Leda clay specimens showed the pore radius to be from 4 to 11 times the thickness of the double layer. Experiments were devised to give a measure of the influence of such ratios and these results are presented in the next section.

RESULTS AND DISCUSSION

Preliminary Studies on the Performance of the Electroosmotic Cell

From equation (1) it may be seen that the osmotic flow should be proportional to the current. Based on average flow rates (Table I) some preliminary trial runs were carried out to test this proportionality for two soils: sample 1, a Leda clay sample of low sensitivity; samples 2 and 2A, Leda clay samples of high sensitivity. Samples 2 and 2A were cut from the same block to check the

TABLE I

Influence of electrical current on liquid flow rate

i, mA	No. 10-min runs	Liquid flow, cc/10 min		Av., cc/10 min	Rate, cc/s $\times$ 10^{-4}
		Left capillary	Right capillary		
Sample 1					
1.2	2	0.0345	0.0333	0.0339	0.57
1.2	2	0.0362	0.0345	0.0353	0.59
2.4	2	0.0719	0.0705	0.0712	1.19
2.4	2	0.0719	0.0710	0.0714	1.19
Sample 2					
2.4	2	0.0703	0.0704	0.0704	1.17
2.4	2	0.0713	0.0700	0.0706	1.18
4.8	2	0.139	0.140	0.140	2.34
Sample 2A					
2.4	3	0.0700	0.0700	0.0700	1.17
4.8	2	0.139	0.140	0.140	2.34

reproducibility of the sample preparation and measurement procedure. Linear proportionality of current and liquid flow was attained by the apparatus as required by equation 1 and the reproducibility was satisfactory within the expected experimental error.

There was some concern also that if there was a repression of osmotic flow, it would reduce the calculated electrokinetic potentials, as mentioned above. Such errors would be greatest at low electrolyte concentrations when the diffuse layer thickness would be near the maximum. Increasing the water content to nearly four times the natural water content, thereby increasing the pore size, did not significantly influence the calculated electrokinetic potential, as is shown in Table II.

TABLE II

Electrokinetic potentials with increasing moisture contents for two soils of widely different sensitivities

Moisture content, %	Dry density, g/cm³	Specific cond., $\lambda \times 10^3$ ohm^{-1} cm^{-1}		E_k, mV
		Of sample	Of bulk pore water	
Sample A1: natural salt concentration, $S = 30$				
65	0.954	1.07	2.25	14.9
115	0.652	1.26	2.25	14.3
161	0.483	1.42	2.25	14.7
213	0.379	1.52	2.25	14.2
Sample A2: electrolyte added				
101	0.708	5.40	11.3	12.1
154	0.505	6.19	11.3	12.8
197	0.407	6.72	11.3	12.8
Sample B1: natural salt concentration, $S = 900$				
52	1.110	1.61	3.96	27.7
68	0.942	1.75	3.96	26.5
90	0.740	2.13	3.96	26.9
105	0.675	2.28	3.96	26.9
Sample B2: electrolyte added				
66	—	5.24	13.4	19.3
89	—	6.19	13.2	18.6
115	—	7.08	12.9	18.0

Influence of Chemical Dispersion

In previous studies (Penner 1963) it was observed that the sensitivity of remolded clay could be greatly increased by adding sodium metaphosphate, a common dispersant used in analyses of grain size. This phenomenon has been attributed to an increase in interparticle repulsion. Theoretically, this should also increase the electrokinetic potential. Table III gives the results of these experiments. The soils were selected from the one salty area found in the Ottawa area. Sample 126-5 had a sensitivity of 34, a natural electrolyte concentration of 9.6 g/liter, and a measured electrokinetic potential of 19.7 in the remolded state. The remolded sample was diluted with several gallons of water, then washed and the solids recovered. This reduced the specific conductivity of the specimen from 6.28×10^{-3} ohm^{-1} cm^{-1} to 0.49×10^{-3}. Removal of salt increased the electrokinetic potential from 19.7 to 23.2 and the sensitivity from

34 to 91. Sodium metaphosphate was then added at the rate of 1 g of salt per 100 g of soil. This increased the electrokinetic potential from 23.2 to 64.6 and the sensitivity from 91 to 2 150. This was repeated with a similar soil slightly higher in the profile with comparable results.

The electrokinetic potential was next measured for various concentrations of sodium metaphosphate on a sample of Leda clay with a low natural salt content. The results given in Fig. 5 show that a decrease in shear strength of the re-molded material by additions of sodium metaphosphate is accompanied by increases in the electrokinetic potential.
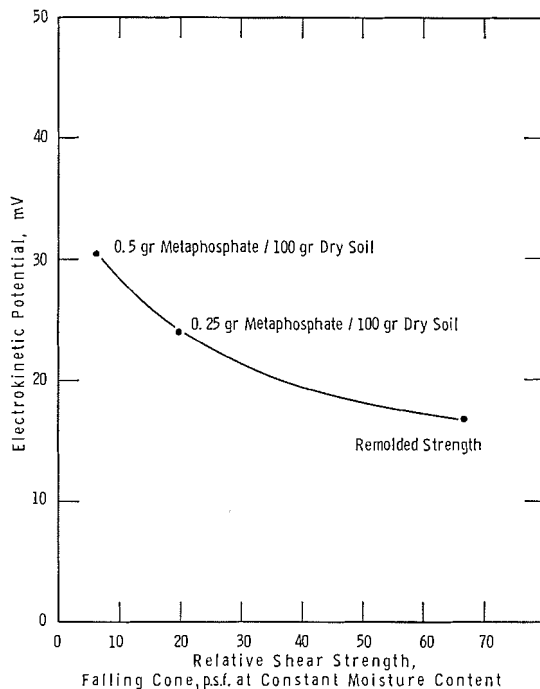
FIG. 5. Shear strength – electrokinetic potential relationships resulting from chemical treatment.

The results shown in Table III and Fig. 5 may be explained as follows. When a flocculated clay mass is remolded with a dispersant such as sodium metaphosphate, the adsorption of the phosphate increases the repulsion forces. By remolding the soil mechanically, the particles held in close association by Van der Waal's attraction or other forces are separated. Once separated, the repulsion is too high to allow the particles to recombine. As the particles strongly repel each other the fluid in the pore spaces distributes itself evenly among the particles, which now behave as separate entities. Even at the field moisture content, samples that become highly sensitive when remolded with sodium metaphosphate tend to settle so that water collects on the surface of the sediment when left standing over a period of days. This is because the face-to-face

TABLE III

Influence of changing the electrokinetic potential E_k of a remolded marine clay (a) by washing out salts and (b) by washing out salts and adding dispersant

Treatment	Moisture content, %	Specific cond., $\lambda \times 10^3$ ohm^{-1} cm^{-1}		E_k, mV	S
		Of sample	Of pore water		
Queensway Overpass 126-5: pore water salt concn. 9.6 g/liter					
Remolded sample	63	6.28	16.9	19.7	34
Washed sample	63	0.49	0.29	23.2	91
Washed and dispersant* added	67	1.16	0.53	64.6	2150
Queensway Overpass 126-4: pore water salt concn. 9.1 g/liter					
Remolded sample	63	4.94	14.6	19.2	45
Washed sample	63	1.88	1.88	25.6	120

*Sodium metaphosphate, 1 g/100 g dry soil.

arrangement of clay particles allows the solids to pack more densely than in the cardhouse arrangement visualized for the flocculated state.

Leaching Experiments

In preliminary studies naturally occurring electrolytes were washed out of highly diluted remolded clays originally containing high salt contents in the pore water. The electrokinetic potentials increased. This treatment, however, was different from the natural leaching process visualized by Rosenqvist (1955).

In our subsequent experiments undisturbed specimens were cut from high salt content clays, and electrokinetic potentials were measured before and after various stages of leaching. The effectiveness of leaching these undisturbed samples was ascertained from resistance measurements of the soil plug and from the conductivity of the leachate. The results are shown in Table IV. The

TABLE IV

Electrokinetic potentials E_k of leached undisturbed samples at field moisture content

Treatment	Specific cond., $\lambda \times 10^3$ ohm^{-1} cm^{-1}		E_k, mV	S
	Of sample	Of pore water		
Experiment A, 126-5: salt concn. 9.6 g/liter				
Before leaching	4.98	15.3	15.2	34
After leaching	0.33	0.46	22.1	
Experiment B, 126-4: salt concn. 9.1 g/liter				
Before leaching	4.19	14.6	16.9	45
After leaching	0.29	—	22.8	
Experiment C, 126-4				
Before leaching	4.50	14.6	16.8	45
After leaching	0.34	—	21.6	
Experiment D, 126-4				
Salts leached out then leached with metaphosphate solution	0.65	1.25	26.2	
Leaching out excess metaphosphate with distilled water	0.56	0.82	30.0	

experiment was repeated three times (experiments A, B, and C) with soil from the same sampling tube. In experiment D, the sample was leached first with distilled water to reduce the salt content, then with a dilute solution of sodium metaphosphate, and finally with distilled water to remove excess dispersant.

It follows from these experiments that simple leaching of salt from marine clays increases the electrokinetic potential and hence the repulsion and sensitivity as predicted by Rosenqvist. It also demonstrates the influence of dispersants on the undisturbed specimens. The full significance of these experiments unfortunately was not realized at the time and no strength measurements were made to determine sensitivity. Since the pattern between sensitivity and electrokinetic potentials has already been established (Table III in this paper for remolded state), the conclusion seems reasonable.

Electrokinetic Potentials of Undisturbed Soils of Varying Salt Concentration

Previous experience with clays from the Ottawa–Hull area has failed to show that for naturally occurring soils of varying salt concentration there was a diminution of sensitivity with increasing salt contents (Penner 1963). This is verified for 16 soils from different locations and depths by the present study. At low salt concentrations of the pore water (4×10^{-3} ohm^{-1} cm^{-1} in terms of specific conductivity) sensitivity may vary enormously. Soils with salt concentrations in excess of this may still vary considerably but did not exceed 75, as is shown in Fig. 6. It is not possible for soils with high salt concentrations to
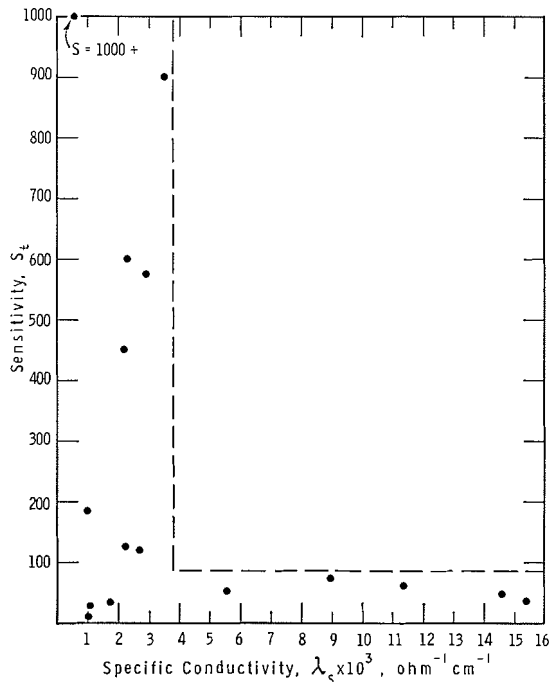

FIG. 6. Salt concentration of the pore water in terms of specific conductivity as a function of sensitivity.

achieve very high sensitivities because of the strong flocculating effect. At low salt concentrations, the sensitivity may be either high or low.

Electrokinetic potentials were determined on the same soils as were used for the experiments recorded in Fig. 6. Taking into account the range in moisture contents, grain size distribution, and percentage of clay content, all of which have a strong influence on sensitivity, the pattern established between sensitivity and electrokinetic potentials is remarkably consistent with the theory of interparticle repulsion (Fig. 7). Other things being equal, the theory would
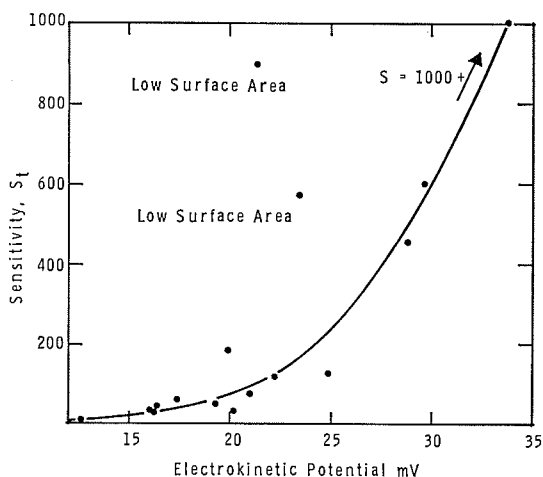

FIG. 7. Electrokinetic potentials of undisturbed Leda clay as a function of sensitivity.

suggest an increasing sensitivity with increasing electrokinetic potential. The two soils that are notable exceptions to the general pattern seem to have too high a sensitivity. They have a relatively low surface area and are therefore relatively coarse in texture, although the clay content as measured by the hydrometer method is similar to that for the rest of the soils. Thus for soils at low pore water electrolyte concentrations a high sensitivity cannot automatically be assumed because other factors determine their behavior.

Factors that Control Sensitivity Other than the Amount of Salt in the Pore Water

One factor that appears to be important to sensitivity is the coarseness of the material. Table V gives percentage of clay size and surface area for the soils studied in detail. Soil samples 94-20-5, 94-27-1, 123-2-3 are much coarser, based on surface area, than might be expected from their clay size content, and all have sensitivities in excess of 500. This is reflected also in their low plasticity indices: 8, 10, and 5, respectively.

The valency of the counter ions (ions of charge opposite the solid) in the pore water has a strong influence on the electrokinetic potential and on all phenomena where the electrical double layer plays an important role. This is known as the Shultz-Hardy rule. As an example Kruyt (1952) cites typical values for other colloids that induce flocculation. The flocculation values range from 25

TABLE V

Electrokinetic potentials for soils listed in order of sensitivity

Soil Code No.	Depth, ft	PI	E_k, mV	S	M.C. %	Clay, %	Area, (m²/g)	Specific cond., $\lambda \times 10^3$
136-2	32	44	12.6	11	75.3	85	77.8	1
94-13-3	22	38	16.2	30	66.9	82	72	1.07
124-19-5	60	17	20.2	33	62.9	77	62	1.78
126-5-4	75	45	16.1	34	62.4	85	72	15.4
126-4-4	65	45	16.4	45	65.3	89	—	14.6
126-1-4	35	40	19.3	53	66.1	78	60	5.61
126-3-4	55	46	17.4	60	63.9	79	66	11.4
126-2-4	45	38	21.0	74	63.8	78	60	8.97
129-16-4	57		22.2	118	80.1	85	85	2.71
124-3-5	12	28	24.9	126	86.6	71	79	2.25
129-7-5	30	32	19.9	183	89.7	79	76	1.02
124-12-5	39	27	28.8	453	83.5	76	79	2.19
94-20-5	53	8	23.5	575	52.5	72	47	2.94
124-9-6	30	24	29.7	600	94.0	86	80	2.33
94-27-1	72	10	21.4	900	50.6	67	54	3.54
123-2-3		5	33.8	1000+	41.0	54	29	0.6

LOCATION:		
Sewer plant	94
Toulnustouc	123
Gloucester	124
Queensway Overpass	126
Breckenridge, Que.	129
Interceptor shaft	136

to 150 millimoles per liter for monovalent ions, 0.5 to 2 for divalent ions, and 0.01 to 0.1 for trivalent ions. It was therefore of importance to examine the chemical nature of the pore water, which was extracted for analysis with the pressure membrane apparatus.

A few total analyses of the pore water were carried out, but emphasis was placed on the six main constituents suggested by Rosenqvist (1955). The pore water contained moderate amounts of dissolved silica and aluminium, and traces of numerous other elements in addition to calcium, sodium, magnesium, potassium, sulfate, and chloride. Table VI gives the percentage of calcium

TABLE VI

Percentage composition based on milliequivalents/liter

	$Ca^{++} + Mg^{++}$	$Na^+ + K^+$	E_k	S
136-2	—	—	12.6	11
94-13-3	47%	53%	16.2	30
124-19-5	13	87	20.2	33
126-5-4	11	89	16.1	34
126-4-4	10	90	16.4	45
126-1-4	9	91	19.3	53
126-3-4	10	90	17.4	60
126-2-4	9	91	21.0	74
129-16-4	—	—	22.2	118
124-3-5	7	93	24.9	126
129-7-5	8	92	19.9	183
124-12-5	5	95	28.8	453
94-20-5	8	92	23.5	575
124-9-6	5	95	29.7	600
94-27-1	6	94	21.4	900
123-2-3	2	98	33.8	1 000+

plus magnesium, and of sodium plus potassium, in terms of percentage composition of the total amount of the four elements in milliequivalents per liter.

The sample from the Sewer plant site (code No. 94, Table V) at 22 ft had a sensitivity of 30, at 53 ft it was 600, at 72 ft, 900. Since the percentage of divalent ions was 47, 8, and 6 respectively, it follows from the Shultz-Hardy rule the sensitivities should fall in this order. The soils at 53 and 72 ft are, in addition, more coarse than those at 22 ft, based on surface area measurements. The sample from the Gloucester location (code No. 124, Table V) at 60 ft was much less sensitive than at 12, 30, and 39 ft. The divalent ion percentage was 13 at 60 ft as compared with 5 to 7% in the upper parts of the profile. For the sample from Toulnustouc only 2% of the ion content were divalent ions which, in addition to coarseness of the material, accounts for its high sensitivity. For a number of the soils, however, the reasons for their position in order of increasing sensitivity were not clear.

CONCLUSIONS

1. Leda clays sampled even within a relatively small area exhibit a large range of sensitivity unrelated to the electrolytic content of the pore water. This has always been considered to be anomalous. Measurements of the electrokinetic potential show that the behavior of these soils is consistent with the double-layer theory of repulsion. Structural breakdown is easier to achieve and the recombination of particles into an open and random structure is more difficult the higher the electrokinetic potential; this results in higher values of sensitivity.

2. It has been shown that both sensitivity and the electrokinetic potential can depend on the nature of the electrolyte, consistent with the Shultz-Hardy rule.

3. Indications are that the coarseness of the material, using surface area measurement as the criterion, has a moderately strong influence on sensitivity. Soils with a smaller than average surface area are more sensitive than finer grained soils at the same electrokinetic potential.

4. The electrokinetic potential of Leda clay increases fairly consistently with increasing sensitivity, based on results for some 16 samples.

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