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A Study on Electro-Osmotic Consolidation of Soft Clays

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SYNOPSIS The effects of an electro-osmotic treatment on a soft sensitive clay from Eastern Canada were examined based on the laboratory tests performed on undisturbed specimens. The interpretation of the tests focus on the non-homogeneity of the treatment, the influence of polarity reversal and strong induration which develops near the anode in addition to the consolidation.

INTRODUCTION

Since Reuss (1808), it is known that water can be extracted from a soil using an electrical potential. Models to describe and predict the movement of water through soils have been proposed for many years [Helmholtz, 1879; Smoluchowski, 1914; Gray and Mitchell, 1967]. In its simplest form, the flow of water in a soil under an electrical potential can be described as:

$$v = k_e \, V/L$$

where v is the velocity, V, the applied potential, L the distance between the electrodes and k_e, the coefficient electro-osmotic permeability. The formulation is analogous to Darcy's law describing the flow of water in a soil under an hydraulic potential. Since the electro-osmotic flow in a soil depends on the surface phenomena of particles, it is almost independant of the pore size and k_e has been found to be fairly similar for most soils with values ranging generally between 2 and 5 x 10^{-5} cm/sec. per V/cm. As for clayey soils, the electro-osmotic permeability is 100 to 1000 times greater than the hydraulic permeability. Therefore, an electro-osmotic treatment appears attractive for the drainage or consolidation of soft clays. Successful and well-documented field applications have been reported since many years [Casagrande, 1949, 1983; Bjerrum et al. 1967; Lo and Ho, 1991].

Soft clay foundation is one of the most classical and universal problems in geotechnical engineering. In an embankment construction, widely used solution consists of consolidating the foundation by means of vertical draines and stage construction. Accelerating the consolidation before the end of construction results in an increase of shear strength of the clay and reduction of settlement after the construction. Large berms remain however necessary to stabilize the foundation during construction and even with vertical drains at close spacings, a period of one or two years has to be allowed for the consolidation.

There are always advantages for a foundation treatment which can be completed before the beginning of construction. A treatment of a soft clay foundation by electro-osmosis theoretically offers the potential of draining and consolidating the foundation before construction, solving the problem of foundation stability and reducing after construction settlement. However, an electro-osmotic foundation treatment is regarded presently with suspicion by geotechnical engineers and is not generally considered as a viable alternative mainly due to the complexity of the treatment and to uncertainties of the results. As it is an important foundation problem in soft clays in Eastern Canada, an extensive research program on electro-osmotic treatment of soft clays has been initiated three years ago at the Université de Sherbrooke. This paper presents results of the initial laboratory tests in the program to illustrate some of the problems regarding electro-osmotic consolidation.

DESCRIPTION OF SOIL AND LABORATORY PROCEDURES

The soil tested in this study program was a marine clay deposited about 8000 years ago in the Tyrrell Sea in Northern Québec. Undisturbed block samples of 25 cm in diameter and 40 cm in height [Lefebvre and Poulin, 1979] were obtained on a terrace along the La Grande River at the LG-1 hydro-electric site in the James Bay area. The properties of the clay are summarized in Table 1.

Clay samples of 8.9 cm in diameter and 17 cm long were cut from the block samples and introduced in a plexiglass cell. Perforated steel plates were placed at each end of the clay cylinder as electrodes. Brass pins along the axis of the cell allowed to follow during the tests the voltage distribution between the electrodes. One end of the cell was fixed while the other end could move under a pressure applied by a piston. The tests were conducted under pressures equivalent to the in situ conditions. A diagram of the cell, along with other installations is shown in Fig. 1. The electro-osmotic tests were performed under controlled voltage and direct current.

TABLE I. Properties of the clay specimens

Depth of samples	11.6 to 14.2 m
Natural water content	57% ± 2%
Clay size fraction (⟨ 2μm)	51%
W_L	35%
W_P	21%
I_P	14%
Initial Cu (fall cone)	40 kPa
Preconsolidation pressure	137 kPa
In situ σ_v'	65 kPa
Specific resistivity	550 ohm-cm
Electro-osmotic permeability	4 x 10^{-5} cm/sec
Conductivity of the pore fluid	1940 μmho/cm

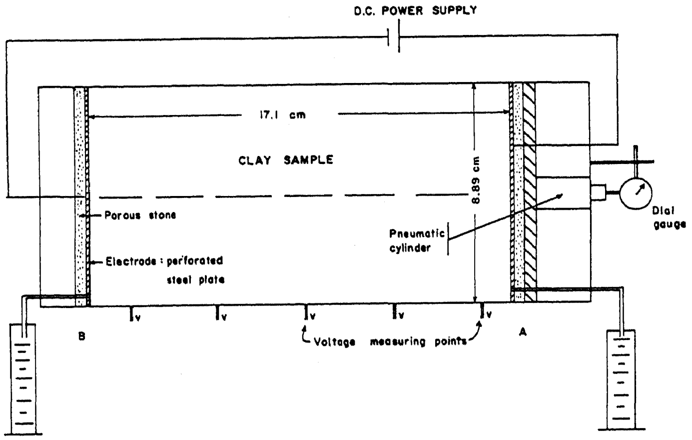

Figure 1. Schematic arrangements for the electro-osmotic tests

Test interpretation

Drainage, axial deformation, current and voltage distributions were monitored during the test. Water content and undrained shear strengths were evaluated after the test at each centimeter along the axis of the clay cylinder and were compared with the initial values. The undrained shear strength was evaluated by using a Swedish fall cone (CAN/BNQ 2501-110-M-86). From the experience on Eastern Canadian clays, the undrained shear strength evaluated by the use of fall cone is very similar to the field shear strength. Atterberg limits were determined after the test at different locations in the clay sample. Some of the characteristics of the tests which would be discussed in the paper are presented in Table 2.

TABLE II. Characteristics of the electro-osmotic tests

Test No.	Depth	Number of polarity reversal	Voltage gradient V/cm	Duration hour	Total energy kWh/m^3	ΔV/V %	Energy 1% ΔV	I_P - plasticity index after test %	
								Anode	Cathode
1	12.6	0	1.5	6	19.0	6.1	3.1	33	Very low
2	14.2	0	0.2 → 0.3	40	4.7	5.0	0.9	27.9	10.2
3	11.9	5	1.0	7	14.9	4.0	3.7	14	14.8
6	13.0	4	0.75 → 1.0	28	30.0	15.0	2.0	28.3	9.2
8	13.7	4	0.2 → 0.6	60	21.2	12.5	1.7	23.0	8.2

One of the main objectives of the initial testing program was to investigate the effect of an electro-osmotic treatment on the undrained shear strength. For a given clay, there is an unique relation between the undrained shear strength and the maximum effective stress applied during the consolidation. The ratio Cu/σ_v' (or Cu/σ_p') does not vary much from one clay to the other and is generally between 0.20 - 0.30 when Cu is evaluated with the field vane or the laboratory cone. The void ratio or the water content can be related to the effective stress using oedometric compression curves. It is then possible to establish a relation between the water content and the undrained shear strength. If after an E-O treatment, the shear strength differs significantly from the values deduced from the water content, the difference thus reflects the influence of factors other than the consolidation.

In the depth interval (11.6 to 14.7 m), where the samples were obtained, the clay was particularly homogeneous. The two oedometric curves (Fig. 2) define a unique relation between void ratio and effective stress. Using a ratio Cu/σ_v' of 0.27 determined for this clay, the relation between water content after consolidation and undrained shear strength is presented in Figure 3 (solid line).

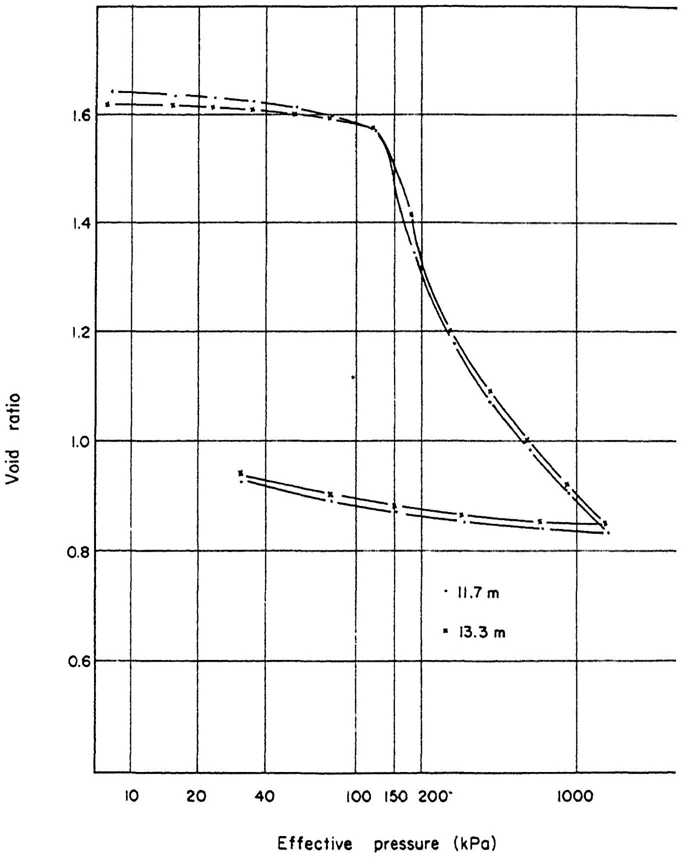

Figure 2. Compression curves in oedometer tests

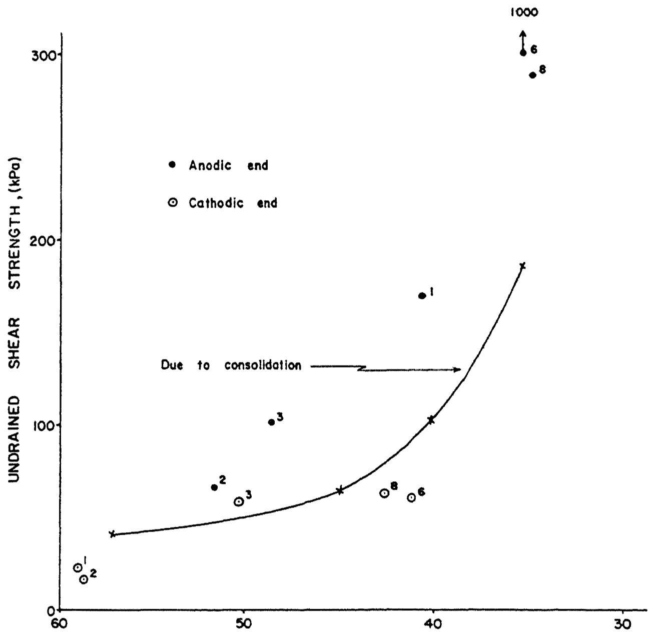

Figure 3. Undrained shear strength as a function of water content

Non homogeneity of the treatment

Results of two standard E-O tests are presented in Figures 4 and 5. Each figure presents the distribution of water content and undrained shear strength after the treatment and the evaluation of drainage during the tests. The first test lasted only six hours but with a high voltage gradient of 1.5V/cm. The second test lasted forty hours with low voltage gradients, starting at 0.2 V/cm and increased to 0.25 and 0.3 V/cm with almost equal time intervals. At the end of the tests, the volume of water extracted was 72 cc and 55 cc for the high and low voltage gradient tests, corresponding to a change of volume of 6.1 and 5% respectively. The rates of drainage decreased by about half towards the end of the tests. However, additional drainages were still possible when the tests were stopped. In the initial phases of the tests, the rate of drainage in the two tests were proportional to the applied voltage gradients (Fig. 4c and 5c). The energy consumption during the tests were 19 and 4.7 kWh/m^3 respectively for the tests with the high and low voltage gradients. For every percentage of volume change, the energy consumption was lower for the test with the low voltage gradient. This is related to the fact that while the drainage is proportional to the voltage, the energy consumption is proportional to the square of the voltage. Thus, even if it takes a longer time, it is cheaper in terms of energy to apply a low voltage gradient.

The decrease in water content was significant at the anode side of the specimen. No reduction of water content was observed in half of the sample on the cathode side (Fig. 4b and 5b). A large increase in shear strength was measured close to the anode. The average water content and undrained shear strength in the two centimeters of the sample adjacent to the anode has been plotted on Fig. 3. The shear strength at the anode was about 40% higher than that expected from consolidation only. In addition to the drainage, the electro-osmotic treatment was producing a significant induration of the clay at the anode side. In fact, for test No. 2, where the water content close to the anode had been decreased only to 52% (Fig. 5b), most of the increase in shear strength was due to induration (Fig. 3).

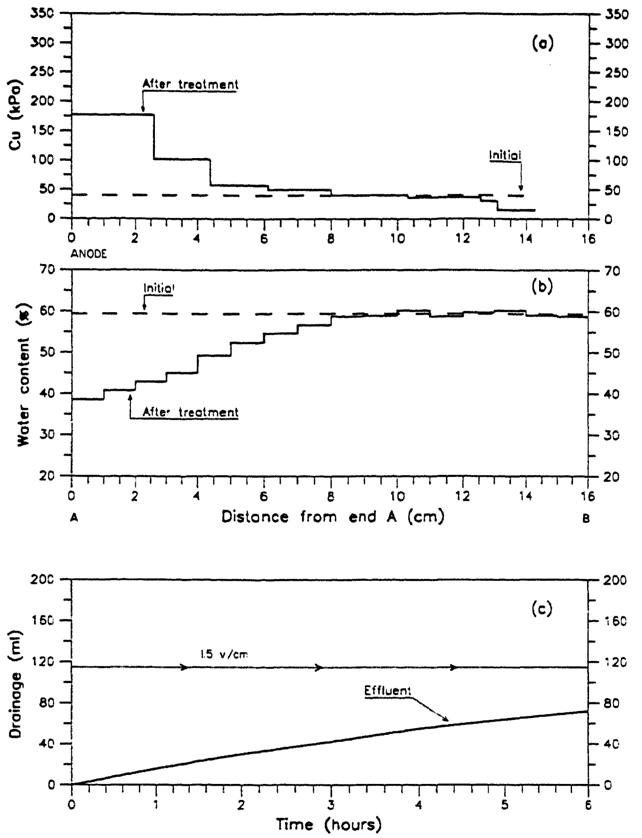

Figure 4: Distribution of undrained shear strength (a) and water content (b) after treatment; Evaluation of drainage during treatment (c); Test No 1, voltage gradient of 1.5 v/cm.

On the cathode side of the specimen, the electro-osmotic treatment had, on the contrary, produced a marked decrease in shear strength of about 40 to 50%. For the Tyrrell Sea clay, part of the measured preconsolidation pressure as well as the in situ undrained shear strength is believed to be due to some interparticle bonding [Lefebvre and Ladd, 1988]. It seemed that the physico-chemical effects associated with the electro-osmotic treatment had altered the interparticle bonding reducing significantly the undrained shear strength on the cathode side where high pH developed during the treatment.

The physico-chemical effects of the E-O treatment were confirmed by the changes in Atterberg limits and sensitivity. The plasticity indices increased after both tests near the anode and decreased near the cathode. The changes, in the Atterberg limits and in the water contents had drastically changed the sensitivity of the clay.

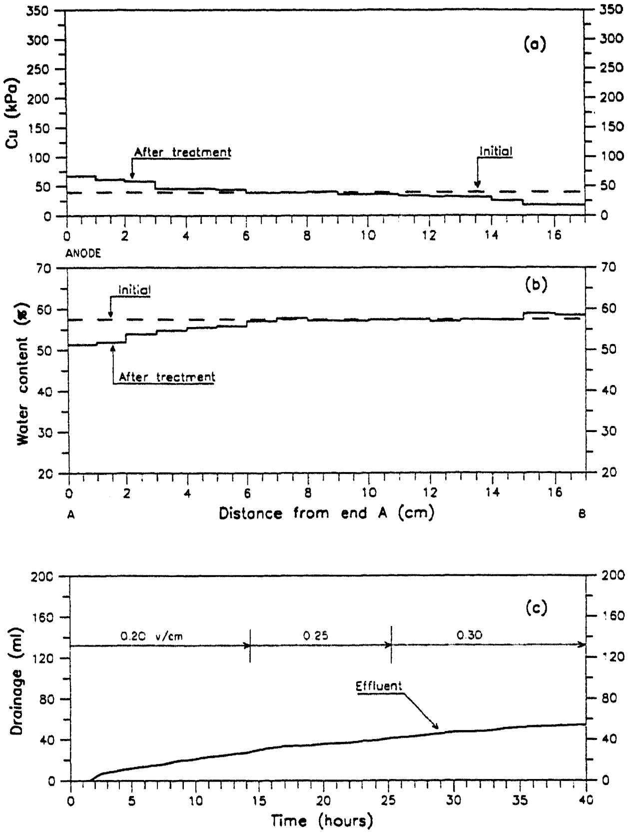

Figure 5: Distribution of undrained shear strength (a) and water content (b) after treatment; Evaluation of drainage during treatment (c); Test No 2, voltage gradient of 0.2 to 0.3 v/cm.

A similar induration at the anode had been observed by Bjerrum et al. [1967], in an E-O field treatment of a soft normally consolidated clayey silt. It had an initial water content of 31% and initial undrained shear strength of only 9 kPa. The effect of the field treatment was well documented in a trench by recording the water content and determination of undrained shear strengths using a small vane. The water content had reduced and the undrained shear strength had increased only at the anodic side (Fig. 6). The relation between water content and undrained shear strength was well documented by Bjerrum et al. Figure 6a compared the actual shear strengths determined after the treatment with those values evaluated from the consolidation test with final water content. One could appreciate that more than 80% of the shear strength after the E-O treatment was due to induration and not due to consolidation.

Reduction of shear strength was also recorded near cathodes during the treatment by field vane borings. However, after the end of the treatment, the shear strength was found to be the same as that of original value near cathodes.

Effect of polarity reversal

If the treatment in the tests presented earlier had lasted longer, one would expect that the drainage could have affected slightly larger portion of the specimen. The treatment however would have remained non homogeneous as observed in the field by Bjerrum et al. [1967]. Therefore, polarity reversal appears as a logical solution to arrive at a more homogeneous drainage. However, considering the observations made in the tests described earlier, it was not evident that the significant induration in the anodic zone would be preserved once it became cathodic after the polarity reversal. Several tests with polarity reversal were run with different durations and voltage gradients. Only a few of them are presented here.

Test No. 3 was run for 7.5 hours with a voltage gradiant of 1 V/cm. Polarity was reversed at about every 75 minutes so that, at the end of the test, the current had been applied in both directions for an equal amount of time. As seen in Figure 7, the water content was reduced at both ends of the specimen (Fig. 7b) but the shear strength was increased only at the end of the specimen which was anodic in the last stage of the test (Fig. 7a). Considering the water content reduction, the shear strength increase was mainly due to induration (Fig. 3). Total energy consumption during the test amounted to $14.9\ \mathrm{kWh/m^3}$ for a total change of volume of 4%.

In terms of energy, the treatment was less effective than those tests No. 1 and 2 (Table 2). Due to frequent polarity reversals, part of the energy was lost in carrying the water back and forth inside the clay specimen. This was probably responsible for the very limited zones of the specimens which were affected by drainage.

Test No. 6 lasted 28 hours with polarity reversal at about every 3.5 hours under a voltage gradient of 0.75 V/cm for the first half of the test and ending with a 14 hour period under a 1 V/cm gradient in the same direction. As seen in Figure 8, this had resulted in a very significant water content reduction throughout the

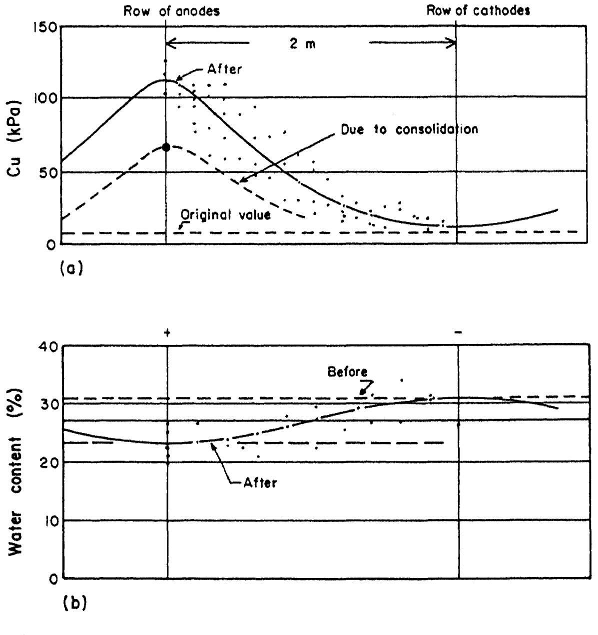

Figure 6. Field distribution of undrained shear strength and water content after 120 days of electro-osmotic treatment (Bjerrum et al. 1967)

sample (Fig. 8b). From an initial value of 58%, the water content had reduced to 35% and 40% for the last anodic and cathodic ends, respectively. On the last anodic side of the specimen, the undrained shear strength evaluated by the fall cone was extremely high in the order of 1000 kPa (Fig. 8a), indicating a very strong induration of the clay, since the shear strength when considering only the water content reduction was in the order of 200 kPa (Fig. 3). On the contrary, for the last cathodic side of the specimen, no shear strength increase was measured even if the water content had been reduced from the initial 58% to 40% after the test. In fact, the shear strength at the end of the specimen was lower than the one expected from the relation of the water content and the shear strength (Fig. 3). During test intervals where the end of the specimen was anodic, the water content was reduced and the shear strength increased. However, the last stage of the test, when the end was cathodic, the physico-chemical effect at that end destroyed the previous induration and decreased the undrained shear strength just similar to the two unidirectional tests presented earlier in the text.

The physico-chemical effects of the last stage were confirmed by a plasticity index which had increased to 28 at the last anodic end and decreased to 9 at the last cathodic end (Table 2). The volume of water extracted during test No. 6 amounted to 160 ml, which was equivalent to a volume reduction of 15%. The total energy consumption during the test was 30 kWh/m^3 or 2 kWh per every 1% volume reduction. Even though the average consolidation for the specimen was relatively high, it should be noted that the shear strength increased only in the half of the specimen.

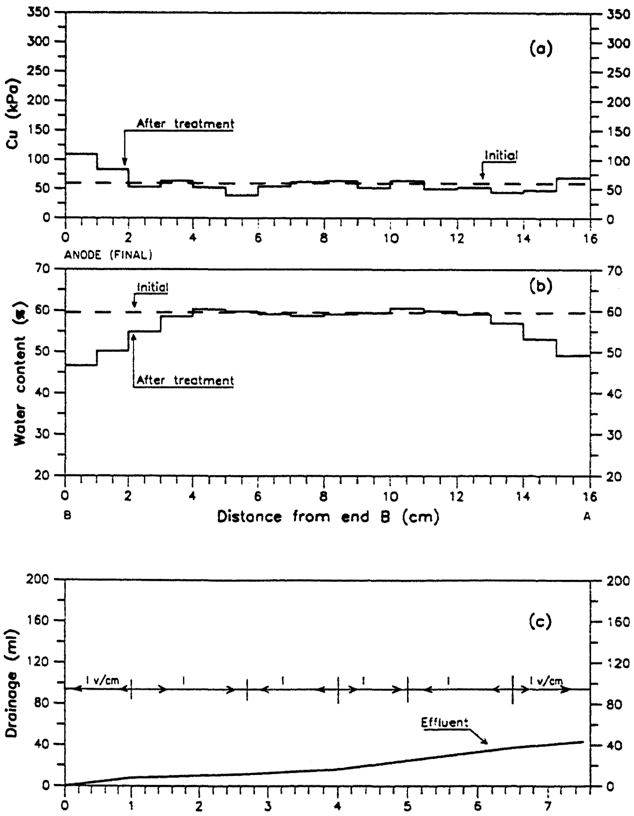

Figure 7: Distribution of undrained shear strength (a) and water content (b) after treatment; Evaluation of drainage during treatment (c); Test No 3, voltage gradient of 1 v/cm.

The test No. 8 lasted 60 hours and ended with two long stages of about 17 hours with reversed polarity under a voltage gradient of 0.6 V/cm. Similar to the previous test, the water content had reduced significantly at both the ends and throughout the specimens. A high increase in shear strength was observed at the last anodic end of the specimen (Fig. 9) largely due to the induration (Fig. 3). A small increase was also measured at the last cathodic end, but lower than that expected considering the water content reduction (Fig. 3). The preponderance of the last stage, on the physico-chemical effects is again evidenced by an increase in the plasticy index to 23% at the last anodic end and a decrease to 8% at the last cathodic end (Table 2). The volume of water extracted during the test amounted to 134 ml, which was equivalent to a volume reduction of 12.5%. The total energy consumption was 21.2 kWh/m^3 or 1.7 kWh for every 1% volume reduction.

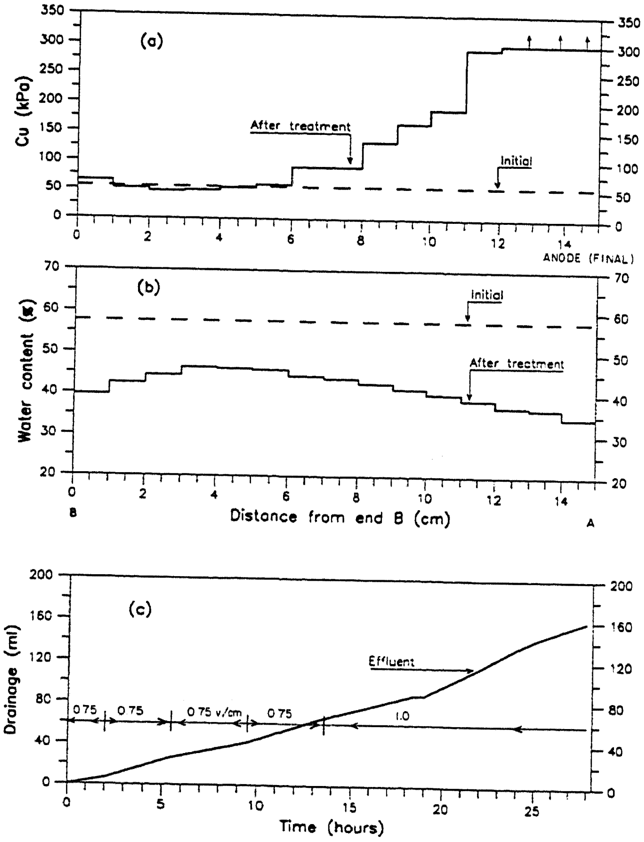

Figure 8: Distribution of undrained shear strength (a) and water content (b) after treatment; Evaluation of drainage during treatment (c); Test No 6, voltage gradient of 0.75 to 1 v/cm.

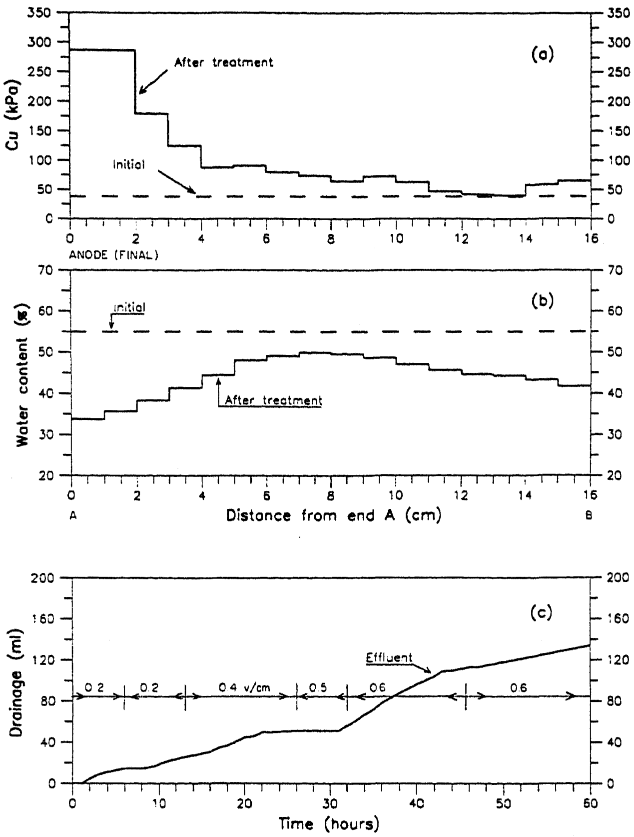

Figure 9: Distribution of undrained shear strength (a) and water content (b) after treatment; Evaluation of drainage during treatment (c); Test No 8, voltage gradient of 0.2 to 0.6 v/cm.

DISCUSSION AND CONCLUSION

The tests presented in the paper were conducted at the beginning of an extensive program on electro-osmotic treatment of soft sensitive clays. The purpose was to gain some understanding on different factors affecting the treatment.

Considerable efforts were put in during this stage on the development of equipments and procedures. The clay had remained saturated throughout the tests presented in the paper and there was a good agreement between the amount of extracted water, the loss of weight of the sample and the loss of water calculated from the changes in the water content. In test No. 2, however, the amount of extracted water was significantly smaller than the loss in weight of the specimen or the loss of water calculated from the changes in the water content. It was believed that some water stored in the anodic porous stone had been sucked into the sample during the test. The recorded amount of drainage however had been extracted out of the sample and was assumed in the interpretation of the test that the amount of drained water would have been the same even if no water had been sucked into the specimen.

The tests indicated a few important qualitative aspects on the electro-osmotic treatment of soft sensitive clays.

1) Unidirectional treatment results in a non homogeneous consolidation between the electrodes. The water content is not reduced at the cathodic zone.

2) Physico-chemistry plays a major role in the shear strength variation following an electro-osmotic treatment. In the zone close to anode, a strong induration is observed in excess of the shear strength compared to the value expected from consolidation only. For the sensitive structured clays where part of the in situ undrained strength is believed to be due partly to interparticle bonding, a unidirectional electro-osmotic treatment results in a significant decrease in shear strength in the zone close to a cathode behaving as if the interparticle bonding has been destroyed.

3) The physico-chemical effects are confirmed by changes in the Atterberg limits. The plasticity index increases in the anodic zone and decreases in the cathodic zone.

4) While the rate of drainage, is proportional to the applied voltage, the importance of the physico-chemical effects appear to be related to the amount of applied energy. Aspects of the physico-chemistry have not been discussed in this paper but the main factors are known to be the pH variation between electrodes, type of electrode metals, composition of the clay and pore water.

5) Polarity reversal results in a much more homogeneous drainage of the clay. The shear strength increase remains however non homogeneous and not proportional to the water content reduction throughout the specimen. The high induration observed in the anodic zone appears to be destroyed when the zone becomes cathodic. Due to physico-chemical effects, the shear strength in the last cathodic zone could be below the value one could expect when considering only consolidation. If the applied energy after the last polarity reversal is sufficient, then the last stage of treatment controls the physico-chemistry, as evidenced by the Atterberg limits.

6) While the shear strength distribution after treatment remains highly non homogeneous, the high induration in the anodic zone, resulting in shear strength locally above 200 kPa, can be interpreted as providing an overall significant improvement of a foundation. The tests, where such high shear strengths have been locally observed, have suffered a volume reduction above 10%. Such a large volume reduction was possible in the laboratory where the electrodes spacing could adjust to the volume reduction. It is not evident however that in the field, soil-electrode contact could be maintained beyond a certain change of volume.

The importance of physico-chemystry, the non homogeneity of the shear strength even after polarity reversal and additional concern of soil electrode contacts in the field, strongly suggest for future approach to focus on physico-chemical aspects and electrolyte injection into the soil to favor further induration as suggested by Esrig (1967) and Gray (1970). Research is presently underway in our laboratory where in, by electro-injection, the shear strength of undisturbed soft clay can be increased above 200 kPa throughout the specimen without polarity reversal.

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