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Soil consolidation using electrically conductive geosynthetics

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ABSTRACT: The paper describes the use of electrically conductive geosynthetic (EKG) materials to consolidate weak fine grained soils. A brief description of the concept of electrically conductive geosynthetics is given as an introduction to a large scale consolidation trial conducted in a specially designed test pit. The results of the trial illustrate the advantages of EKG consolidation over conventional methods which include the ability to treat extremely weak materials. The rate of treatment and the increase in shear strength resulting from electro-osmotic consolidation are shown to be an order of magnitude greater than that which can be achieved using conventional consolidation treatments.

1 INTRODUCTION

It has been found that new uses and applications of geosynthetics can be created by incorporating electro-kinetic phenomena with the traditional functions of geosynthetic materials. This entails the development of a new range of geosynthetic materials (or geocomposites) that are electrically conductive. An electrically conductive geosynthetic is referred to as an electro-kinetic geosynthetic (EKG), Hamir *et al* (2001). Potential applications of EKG materials include: the in-situ decontamination of contaminated soils; the electro-kinetic transport of nutrients in soil; the treatment of waste; the improvement in the performance of lime piles; improvements in reinforced soil technology; and accelerated consolidation of soil.

This paper describes a large scale trial of the consolidation of a slurry using EKG in the form of wick drains using the principle of electro-osmosis.

2 CONSOLIDATION THEORY

When a current is applied to saturated fine grained soils the electro-potential developed between the electrodes causes water to flow from the anode to the cathode through the soil mass. The phenomenon in termed electro-osmosis. There are a number of theories relating to electro-osmosis; that known as the Helmholtz-Smoluchowski theory is the earliest and most widely used, Mitchell (1991).

The electro-osmotic flow, q_e, produced by an applied electrical field is given by the expression:

$$q_e = k_e i_e A \tag{1}$$

where k_e is the electro-osmotic conductivity, A is the cross-sectional area and i_e the voltage gradient.

Equation (1) is analogous to Darcy's Law of fluid flow. However, contrary to the case of hydraulic conductivity, k_h, the electro-osmotic conductivity, k_e, is independent of pore size. By comparing the magnitude of the hydraulic and electro-osmotic permeability of a soil it can be seen that electro-osmosis presents an effective method of removing pore water from soil of low permeability such as clay or silt resulting in consolidation accompanied by a strength gain in the soil. The effect is permanent and achieved in a relatively short time, Milligan (1994).

The economy and efficiency of electro-osmosis is governed by the amount of water transferred per unit of charge passed. It is quantified by the electro-osmotic water transport efficiency, k_i, which is related to the electro-osmotic permeability by the equation:

$$k_i = \frac{k_e}{\sigma} \tag{2}$$

where σ = electrical conductivity of the soil.

Field applications on soil with conductivities in the range 0.002 to 0.003 siemens/mm have proved successful, but treatment on soil with a conductivity of 0.025 siemens/mm is unlikely to be effective, Mitchell (1993). The specific conductivity of soil changes with water content, cation exchange capacity and the free electrolyte content of the soil and is also related to the prevailing chemistry during electro-osmosis, Acar *et al* (1991), Gray and Mitchell (1967).

A theoretical explanation of electro-osmotic consolidation has been presented by Esrig (1968), based upon the development of pore water pressures resulting from the application of a uniform potential field. The theory has been validated by Wan and Mitchell (1976). It is based on the assumption that flow caused by an electrical field may be superimposed on flow caused by an hydraulic gradient. The nature of the pore pressure developed depends upon the boundary conditions at the anode and the cathode. Under normal consolidation conditions these would be: anode closed, cathode open. In this case water is not replaced at the anode, resulting in the development of negative pore pressure, U_e, where:

$$U_e = -\frac{k_e}{h} \gamma_w \cdot V \tag{3}$$

where V is the applied voltage.

3 CONSOLIDATION TRIAL

The trial was conducted in an indoor test facility at a scale such that full scale EKG materials could be used and positioned at spacings representative of the requirements of practical applications. The facility consisted of a test pit measuring 2.4 m in length, 0.93 m in width and 2.4 m in depth which could accommodate 5.4 m^3 of soil, Figure 1. The test pit was constructed with an impervious membrane lining to reduce water loss. Computer controlled monitoring facilities provided details of the rate of consolidation and internal differential settlements.

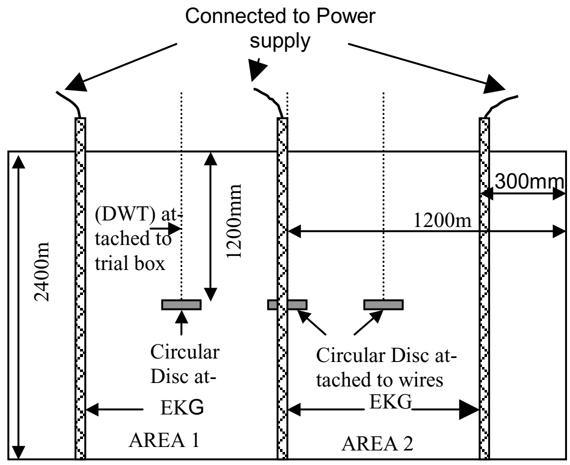

Figure 1. Side elevation of trial box (not to scale).

3.1 *Soil*

Pureflo S Powdered China Clay was used as the test soil. This material has properties similar to Kaolin Grade E. The conductivity of the material was determined using the procedure detailed in BS 1377: Part 3 (1990).

The clay soil was mixed to a water content of 85 percent in a 6 m³ ready-mix truck and poured into the test pit. A vibrating poker was used to dispel any air voids. A total of 5.36 tonnes of clay and 4.55 tonnes of water were required to fill the test pit. With a water content of 85 percent, the test soil can be classified as being a super soft soil in which the shear strength of the material is less than at the liquid limit, Fakher *et al* (1999). Once the clay fill had been placed in the test pit the EKG electrodes were installed by being pushed down from the surface into the clay using a procedure similar to that used for the installation of conventional wick drains. The location of the EKG electrodes (e-PVDs) is shown in Figure 2. Figure 2 also shows that the test cell was divided into two areas, Area 1 and Area 2.

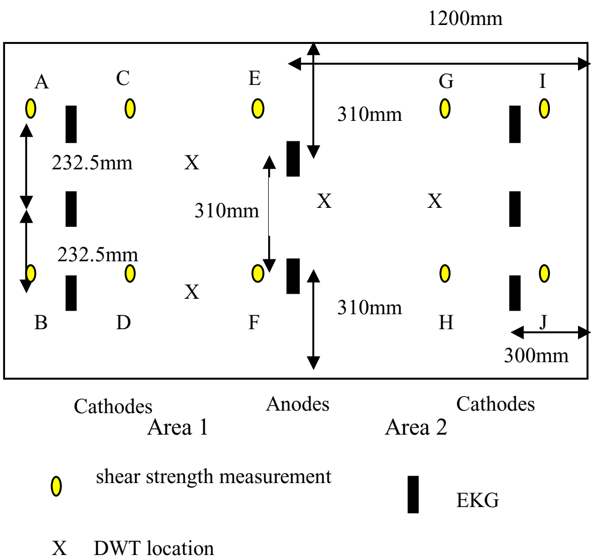

Figure 2. Position of EKG electrodes in trial cell, location of the settlement changes (DWT) and shear strength measurements (A-J)

3.2 *Water Extraction*

During induced consolidation, water is expelled from the clay. This can occur due to normal consolidation under the self-weight of the fill or through electro-osmotic forces. The water extracted was collected in a sump that was formed at one end of the test pit outside the line of the cathode electrodes. Shallow channels along the sides of the clay fill were formed to permit easy run-off of water to the sump. The expelled water was removed using a siphon.

3.3 *Settlement*

Measurement of settlement of the surface of the clay during the test was undertaken using direct measurements. Internal movement of settlement was undertaken using Draw Wire Transducers (DWT). The location of the DWTs is shown on Figure 2.

3.4 *Shear Strength*

In addition to settlement, the development of shear strength was measured at specific locations at depths of 0.5 m, 1.0 m and 1.5 m, using an Inspection Vane Borer capable of measuring shear strength values in the range 0 to 20 t/m², Figure 2.

3.5 *Electrical Current*

The EKG electrodes were connected to a 60V (2A) DC power supply producing an electrical potential between the electrodes of 0.05 V/mm. Details of the current supplied to each Area were recorded digitally and the voltage was kept constant throughout the test period. At the end of the initial test period, the polarities of the electrodes were reversed. No current was supplied to Area 2 which acted as a control. Following polarity reversal measurements of settlement, water extraction, current details and shear strength development were continued.

4 TEST RESULTS

4.1 *Volume and Rate of Water Extracted: Initial Test*

After filling the clay in the test pit it was left to rest for a period of 100 hours. During this period normal consolidation took place and 50 litres of water was expelled equivalent to a surface settlement of 20 mm.

Once an electric potential was applied to the electrodes the rate of extraction of water increased, Figure 3. During the first phase of the test (500 hours) the total water extracted from the test pit was 832 litres, and the volume of the material in the test pit reduced by 0.920 m³, equivalent to 929 litres. This leaves a difference in volume of 97 litres which was determined as being the volume of water which hydrolised as a result of electrolysis, where:

$$4\ H_20 \rightarrow 4\ H^+ + 4\ 0H^-$$

and $4\ H+ \rightarrow 2\ H_2$

$$4\ 0H^- \rightarrow 2\ H_2 + 0_2$$

Thus the quantity of hydrogen and oxygen gases produced equated to 0.065 m³ and 0.032 m³ respectively.

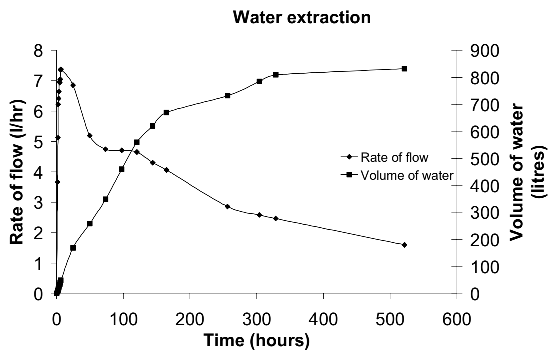

Figure 3. Water extraction.

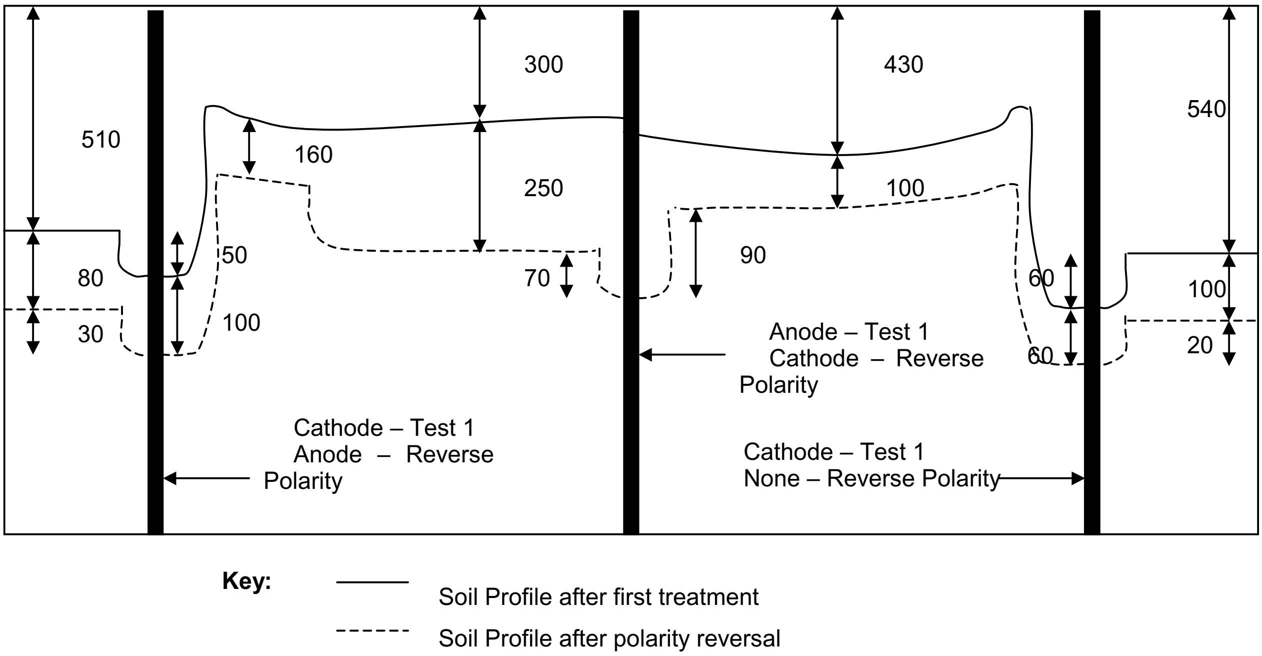

Figure 4. Comparison of surface profile of the clay after first treatment and following polarity reversal (not to scale).

4.2 *Settlement of the Fill*

The initial normal consolidation settlement of the fill over a period of 100 hours was a uniform settlement of approximately 20 mm. After the application of an electrical potential between the EKG electrodes the settlement of the surface of the fill accelerated. The settlement profile of the surface after 500 hours of treatment is shown in Figure 4.

4.3 *Electrical Current*

The electrical potential was kept constant at 60 V. With time the current in Areas 1 and 2 reduced, Figure 5. Figure 5 shows that the current had to be switched off twice between 100-200 hours in order to make repairs to two DWTs when the wires corroded away. Following reapplication of current a temporary initial increase in current was observed.

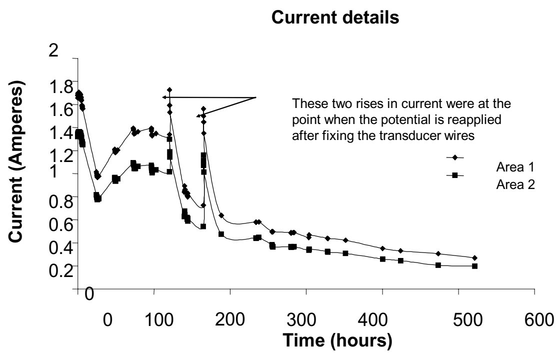

Figure 5. Current profile during the first phase of the trial.

4.4 *Shear Strength*

The shear strength of the clay fill was less than 1 kN/m² at the start of the test. During the application of current the shear strength increased substantially, with a maximum recorded strength after 500 hours of 35 kN/m² in the region of the anode, Figure 6.

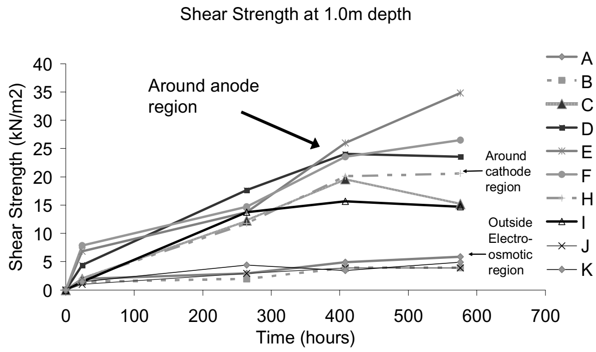

Figure 6. Development of shear strength of clay (1.0m depth).

5 REVERSE POLARITY

5.1 *Volume and Rate of Water Extracted*

The volume of water and rate of extraction following polarity reversal was significantly less than that removed in the initial electro-osmotic treatment – 59 litres (compared to 832 litres). However, the volume of the material in the test cell reduced by 0.342 m³, equivalent to 342 litres of water. The difference in water extracted and the reduction in volume was 283 litres which was deduced to be given off as gases.

5.2 *Settlement of the Fill*

The settlement of the fill following polarity reversal continued, although voltage was only applied to Area 1. The total surface of the clay continued to settle, Figure 4.

5.3 *Shear Strength*

The most significant change to be produced by reversing the polarity of the electrodes in Area 1 was the increase in the shear strength of the fill material to more uniform values. Interestingly the shear strength of the material in Area 2 also increased in value, Figure 7.

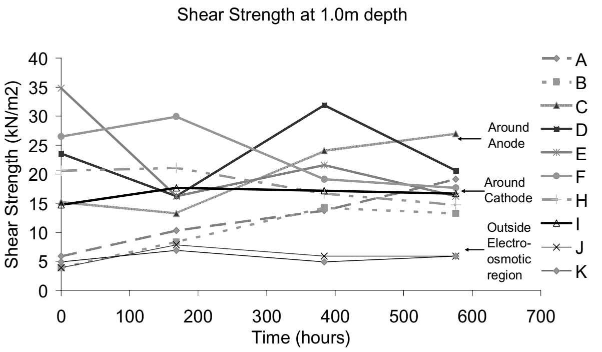

Figure 7. Development of shear strength of the clay after polarity reversal (1.0m depth).

The results of the consolidation trial are summarised in Table 1.

Table 1. Results of consolidation tests

Test condition	Treatment length (hours)	Water extracted (litres)	Gases extracted (litres)	Shear strength (kN/m)	Surface settlement[2] (mm)
Normal consolidation	100	50	-	-	20
Phase 1: Electro-osmosis[3]	500	832	97	anode: 30 cathode: 20 outside treatment zone: 7	395
Phase 2: Electro-osmotic Polarity Reversal[3]	800	59	283	anode: 30 cathode: 20 outside treatment zone: 10	145

Notes: 1. Range of shear strength recorded at a depth of 1.5 m
2. Settlement of surface recorded as an average (total settlement 560 mm)
3. Potential applied 60 V and maximum of 2 amperes

6 DISCUSSION

The results of the trial showed that the use of EKG electrodes to induce electro-osmotic consolidation was successful. The rate of extraction of water under electro-osmotic consolidation was an order of magnitude greater than that which could be produced by normal consolidation. Using normal consolidation theory the surface settlement would not exceed 140 mm which would take 1,110 hours to achieve. The volume of water removed using the e-PVD electrodes was 1,271 litres or 363 percent of that which could be theoretically removed using normal consolidation methods.

The volume of water extracted after polarity reversal was modest, but the reduction in volume continued. It appears that after polarity reversal the proportion of water removed in the form of gases increased. Support for this observation is given by Martinez-Ruiz (2001) in a study on closed-cell electro-osmosis.

The settlement profile of the surface of the fill is unusual and unexpected. Settlement behaviour is clearly more complex as inspection of Figure 4 shows. The influence of porewater pressures within the fill generated by the electric field appear to have a dominant role. This subject is being investigated further.

Settlement of the fill following polarity reversal was expected to be confined to Area 1 as only this Area was subjected to voltage. Again the observed result was significantly different to that expected, Figure 4.

The development of shear strength in the fill from a value of less than 1 kN/m² to values within the treated zone of 7-30+ kN/m² is significant. The value of polarity reversal may have limited benefit in increasing the shear strength between the electrodes but does increase strength outside the treated zone. The increase in shear strength outside the treated region can be explained by pore water pressure development.

The corrosive environment of the clay fill subjected to electro-osmotic treatment was clearly illustrated by the very rapid corrosion of the draw wires of the settlement measuring gauges. The first failure resulting from complete corrosion occurred after 100 hours of current flow. No deterioration of the EKG electrodes was observed during the period of the trial.

6.1 *Power Consumption*

The reduction in water content of the fill was directly proportional to the power consumption. During the first phase of electro-osmotic treatment the total power required was approximately 130 MJ expended over a period of 500 hours. During the second phase after polarity reversal less benefit was achieved and the power consumption was 90 MJ in a period of 800 hours.

7 CONCLUSIONS

The following conclusions can be drawn from the consolidation trial:

- The use of EKG electrodes as an electrically prefabricated drain (e-PVD) is effective and efficient.
- The use of EKG electrodes (e-PVD) can produce significant and rapid increase in the shear strength of very soft fill.
- The use of polarity reversal is beneficial in producing uniform shear strength conditions of the fill.

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