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A full-scale field trial of electrokinetically enhanced cohesive reinforced soil using electrically conductive geosynthetics

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ABSTRACT: The use of cohesive fill in reinforced soil construction is not permitted by most design codes, including the current British Standard on reinforced soil BS 8006: 1995. This paper reviews a full-scale field trial utilising electrokinetics to improve the strength of reinforced cohesive fill *in situ* within a reinforced soil wall, allowing construction with a material that is currently classified as unsuitable. In the trial the cohesive fill was dewatered using horizontally placed electrokinetic geosynthetic electrodes and drains at an applied potential difference of 30 volts within a conventional, sandbag faced, wraparound reinforced soil wall. Results show that the fill within the electrokinetically treated zone of the structure was significantly improved, resulting in a stable structure.

1 INTRODUCTION

The ability of electrokinetic phenomena to transport water, charged particles and free ions through fine grained, low hydraulic permeability soils has been well established following their discovery by Reuss (1809). Electrokinetic phenomena will occur in any soil. However, in medium to coarse-grained soils they provide a less effective transport mechanism than conventional hydraulic flow, due to the high hydraulic permeability (k_h) of these soils, in comparison to the electro-osmotic permeability (k_e) which is used by electro-osmotic flow (Nettleton *et al*, 1998).

In 1939, Casagrande (1952) demonstrated that applying electrokinetics to fine-grained soils with high water contents resulted in an increase in the effective stress within the soil through the generation of negative pore water pressures, increasing its shear strength to such a degree that steep cuts for railway cuttings were able to remain stable. Since then there have been many applications of electrokinetic phenomena in field projects including: improvement of excavation stability, electrochemical induration/hardening, fine-grained soil stabilisation, consolidation, densification and electro-remediation (Pamukcu, 1996).

This paper describes the first known employment of electrokinetic phenomena to reinforced soil.

2 ELECTRO-OSMOTIC THEORY

When a direct current (D.C.) electrical potential difference is applied across a wet soil mass ion migration takes place. Positive ions (cations) are attracted to the cathode and repelled from the anode and negative ions (anions) are forced in the opposite direction. As the ions migrate they drag with them their water of hydration and exert a viscous drag upon the free pore fluid around them. Since there are more cations than anions in a typical soil, composed of negatively charged clay particles, there is a net flow of pore fluid towards the cathode (Pamukcu, 1996).

Although the Helmholtz-Smoluchowski theory (Helmholtz, 1879; Smoluchowski, 1914) was one of the earliest suggested for electro-osmosis it is still one of the most widely used (Mitchell, 1993). The electrical condenser analogy adopted by this theory assumes that the soil capillaries have charges of one sign on or near the surface of the wall (-ve) and countercharges (+ve) concentrated in a double layer protruding a small distance from the wall, the remaining void is assumed to be filled with free pore fluid, as shown in Figure 1.

Upon the application of an electrical potential difference across the system the mobile shell of counter-ions is assumed to drag water through the capillary by plug flow, resulting in a high velocity gradient between the two plates of the condenser. The rate of water flow is controlled by the balance between the electrical force causing water movement in one direction and friction between the liquid and the wall in the other. The overall flow (q_A) generated by the application of a potential difference (Δ) may be expressed as (Mitchell, 1993):

$$q_A = k_e \frac{\Delta V}{\Delta L} A \tag{1}$$

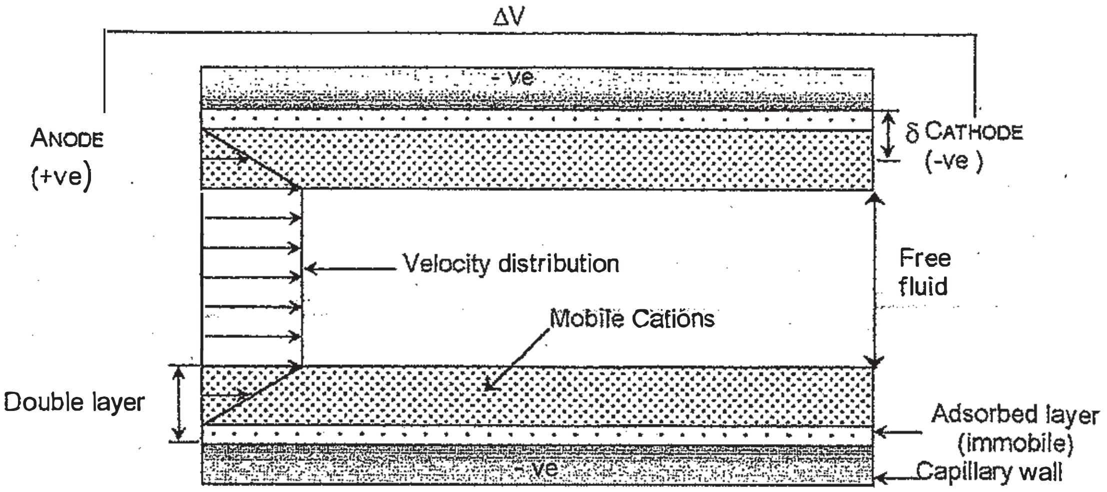

Figure 1. Helmholtz-Smoluchowski Model for electro-osmotic flow (After Mitchell, 1993).

where k_e is the electro-osmotic permeability of the soil; $\Delta V / \Delta L$ is the electrical potential gradient; and A is the cross-sectional area of the soil sample across which the potential difference is applied.

3 COHESIVE REINFORCED SOIL AND ELECTROKINETICS

Many codes of practice do not permit the use of cohesive soils in the construction of reinforced soil structures for permanent works. The reasons given are the potential problems of low strength, high moisture content, creep and low bond strength between the reinforcement and the soil (Jones *et al*, 1997). Laboratory and full-scale field trials of reinforced soil incorporating non-permeable reinforcement have demonstrated that the incorporation of reinforcement into the soil can result in a reduction of the overall strength of the structure. This is due to a rise in the pore water pressure in the vicinity of the soil/reinforcement interface during shearing as observed by Ingold (1981). If permeable reinforcement is used, as opposed to non-permeable, then, although the structure may be approaching drained conditions at the soil/reinforcement interface, the remainder of the cohesive fill may be experiencing undrained conditions and may be failing. The full-scale trail embankment reported by Tatsuoka and Yamauchi (1986) using permeable reinforcement demonstrated this phenomena. Figure 2a shows the reinforcement configurations for both sides of the reinforced trial embankment and Figure 2b shows the resulting displacements of the embankment. It is apparent from the deformed shape of the embankment that the left-hand side reinforcement spacing was too large and hence the pore water pressures were unable to dissipate during loading, thus causing the wall to deform. The right-hand side, however, had a closer spacing of the reinforcement and hence each reinforcing layer took less load. In addition the drainage path length for the dissipation of excess

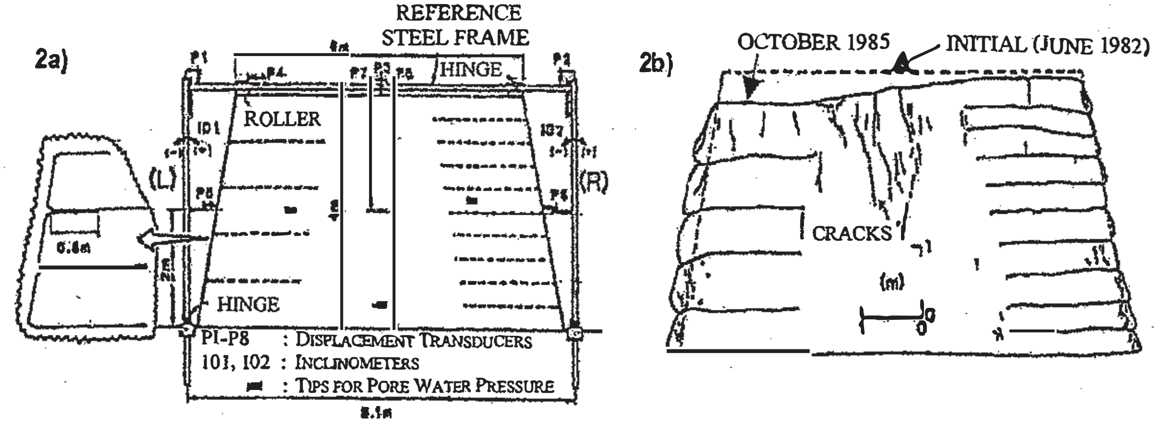

Figure 2a & b. Full-scale reinforced cohesive embankment (After Tatsuoka and Yamanuchi, 1986).

pore water pressure was reduced, thus preventing a build-up of excess pore water pressure; as a result the wall underwent less deformation.

From this and other published literature (Murray and Boden, 1979; Ingold, 1979&b; Heshmati, 1993; Boardman, 1999) it is apparent that if the undrained shear strength (c_u) and pore water pressures within reinforced cohesive fill can be controlled then the use of cohesive fill in reinforced soil would be a more viable option. Electrokinetic phenomena have been shown to dewater cohesive soils successfully, thus causing a decrease in water content and an increase in c_u through an effective overconsolidation of the cohesive soil in the vicinity of the anode. Additionally, due to a decrease in the water content the pore water pressure coefficients A and B are reduced, such that any increase in total stress generates a smaller increase in excess pore water pressure (Craig, 1992). Furthermore, due to electro-chemical changes that take place within the soil during electrokinetic treatment, an increase in shear strength of up to 80% greater than that which can be obtained from an equivalent increase in effective stress alone may be achieved (Bjerrum *et al*, 1967). Hence there is an apparent synergy between these two technologies.

The use of electrokinetic phenomena requires the use of electrodes to apply the electrical potential difference across the soil mass to be treated. Conventional metallic electrodes experience oxidation at the anode resulting in degradation of the electrode itself and an increase in the soil electrode resistance. This results in an overall loss of electrical efficiency within the system.

The electrodes utilised in the trial were electrokinetic geosynthetic (EKG) materials (Nettleton *et al*, 1998). The benefits of using EKGs as opposed to metallic electrodes include: flexibility of the electrode allowing easy manhandling and installation during construction, ease of connection to power supply, greater surface area for soil/electrode contact and better durability. The EKG electrodes used in the trial are described in Rowe and Jones (2000).

4 CONSTRUCTION OF THE WALL

The wall was constructed using a wraparound design, utilising sandbags for the front face to temporarily retain the cohesive and granular fills. The ends of the cohesive trial wall were retained using conventional reinforced soil blocks. A small trial section was constructed at one end of the wall contemporaneously with the main trial; electrodes and drains were also incorporated into this zone but no electricity was supplied to this zone such that it acted as a control. This area was retained on one side using geosynthetic gabions. Figure 3 shows a schematic of the overall trial wall.

The main cohesive trial section of the wall was subdivided into three zones, with each having an electrode spacing of 1.2m, 0.8m and 0.4m respectively. Geosynthetic drains were placed midway between the electrodes to give a drainage path for the excess pore water pressure. The reason for different electrode spacing was to achieve different electric field intensities, thus a variation in ΔV in Equation 1 could be achieved using a single power source. the electrical potential applied across the electrodes was 30 Volts D.C. This gave voltage gradients of 0.45, 0.6 and 0.83V/cm based upon the anode/cathode spacing. The actual 2-D potential gradients calculated using finite difference analysis were slightly less than this due to the loss of potential difference around the electrode/soil interface.

The wall was constructed using a staged construction technique, such that if a single lift of clay was constructed and dewatered vertically by electro-osmosis applied via horizontally placed electrodes and drains. Once this lift had been successfully treated then the next lift was constructed, and so on

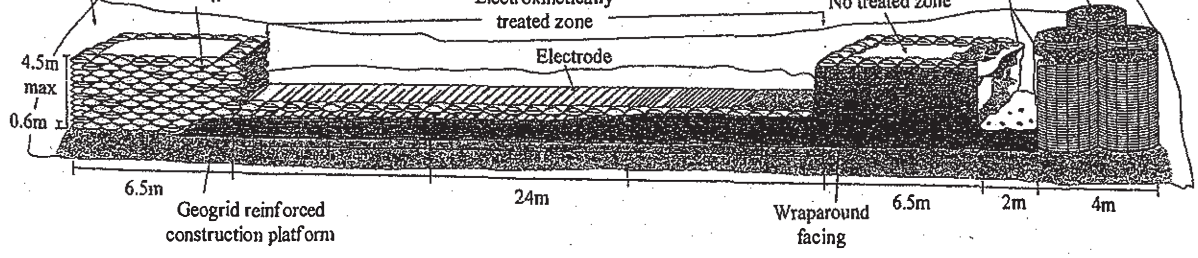

Figure 3. Schematic of wall.

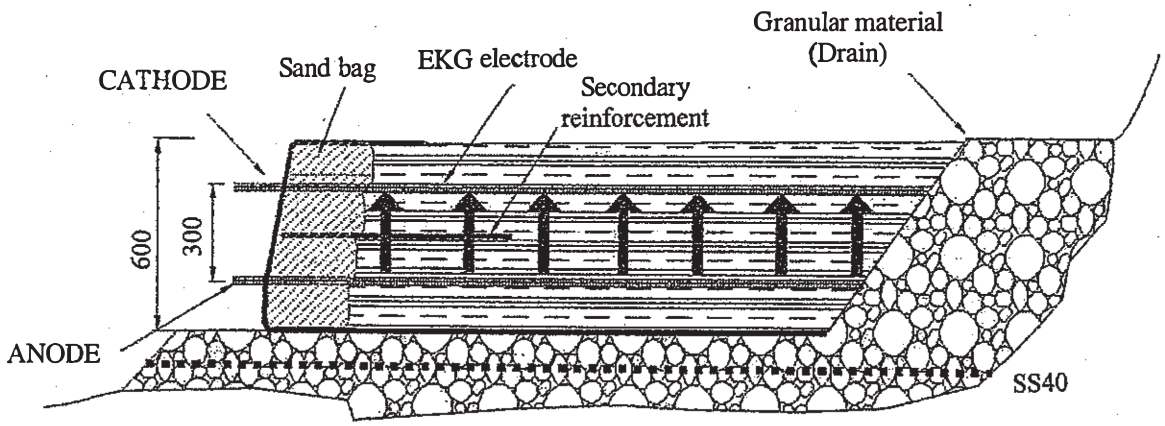

Figure 4. Detail of single lift.

until the full height of the wall was achieved, a total of 8 lifts. Figure 4 shows a detail of the first lift in the cohesive region of the wall.

5 MONITORING AND RESULTS

During the construction of the wall the voltage, current and generator fuel consumption were monitored for each lift. In addition the undrained shear strength of the cohesive section was monitored using a hand shear vane at different treatment times. The results from the hand shear vane for the first lift of construction taken at a depth of 0.25m into the clay are given in Figure 5. A summary of the percentage improvement in strength at 0.25m and 0.5m depth into the first lift for all cohesive zones and the control zone is given in Table 1.

Table 1. Percentage improvement in shear strength of first lift after 278 hours of treatment.

Electrode spacing	0.25m depth	0.5m depth
1.2m zone	16%	7%
0.8m zone	36%	31%
0.4mzone	99%	57%
Control zone	27%	4%

6 CONCLUSIONS

The electrokinetically treated zones of the wall showed increased improvement over the control zone in the wall as demonstrated in Figure 5 and Table1. With successive lifts further improvement took place in underlying lifts due to surcharge loading and drainage through the redundant EKGs and drains. The results have also demonstrated that the electrode spacing and applied voltage gradient is

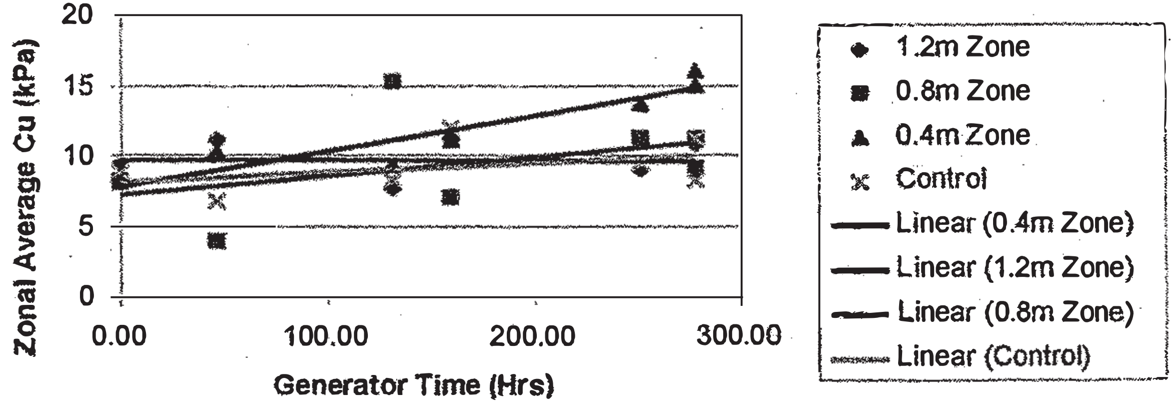

Figure 5. Shear vane results at 0.25m depth for first lift of wall.

critical in order to achieve successful treatment of the cohesive fill *in situ*. The initial results demonstrate that electrokinetic techniques can indeed be used to improve the performance of reinforced cohesive soil. The forensic study of the trial is continuing.

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