Reinforced Soil Using Cohesive Fill and Electrokinetic Geosynthetics

S. Glendinning[1]; C. J. F. P. Jones[2]; and R. C. Pugh[3]

Abstract: An electrokinetic geosynthetic (EKG), is a polymeric geosynthetic material, enhanced to conduct electricity, which can be used to transport water in fine-grained soils by electrokinetic means. This paper describes the design, construction details, and analysis of a reinforced soil wall using EKG and wet cohesive fill. In order to establish an initial design layout, a long-term stability analysis of the wall was carried out using the soil's critical state shear strength parameters. The long-term design was then checked for short-term stability based upon a minimum required undrained shear strength for the clay utilizing four different short-term analytical methods: critical height, Coulomb, discrete theory, and composite theory. The electroosmosis design was then undertaken, based upon the water content—undrained shear strength curve for the fill material ascertained from laboratory testing. Using this curve the difference between the as-placed water content and the water content corresponding to an undrained shear strength of 20 kPa was calculated, giving the volume of water that needed to be removed from each lift of clay fill. Using this volume of water the electroosmosis calculations were undertaken. A simplistic analysis was undertaken using a linear voltage gradient and fixed soil parameters, followed by a more complex analysis using finite difference techniques to establish the voltage gradient. The variation in the value of electro-osmotic permeability k_e were estimated using both an empirical model and a graphical interpretation of the actual variation of k_e measured in the laboratory. The results of these analyses yielded estimated treatment times and undrained shear strength of the clay.

DOI: 10.1061/(ASCE)1532-3641(2005)5:2(138)

CE Database subject headings: Electrokinetics; Geosynthetics; Soil stabilization; Fills.

Introduction

The modern concept of earth reinforcement and soil structures was postulated by Casagrande, who idealized the problem in the form of a weak soil reinforced by high strength membranes laid horizontally in layers. Polymeric and grid reinforcements were developed in the 1970s. These provided enhanced soil/reinforcement interaction and in the case of polymeric materials permit the use of lower quality (cheaper) and waste materials as backfill (Jones 1990, 1996).

The acute lack of conventional frictional fill in some parts of the world has lead to the use of cohesive soils in major reinforced soil structures in theses countries. However, experimentation with the use of cohesive and waste fills concluded that the excess pore water pressures generated in the fill during construction created high horizontal pressures, inhibited the development of effective stress, and so reduced the bond between soil and reinforcement. With increasing proximity to the face of the wall, where draining can occur, and with increasing time, these problems are alleviated. The solution, therefore, has been to include a drainage layer alongside the reinforcement. However, acceptability of the use of cohesive fill is still limited by its hydraulic permeability and its initial water content, so severely restricting the range of materials utilised in practice. Most codes of practice, including *BS8006* (BSI 1995) do not permit the use of purely cohesive soil in the construction of reinforced soil structures for permanent works, with the reasons for its exclusion stated as: low strength, high moisture content, high creep, and low bond strength between the soil and the reinforcement.

Jones et al. (1996) and Nettleton et al. (1998) introduced the concept of electrokinetic geosynthetics (EKG), a range of geosynthetic materials that, in addition to providing filtration, drainage, and reinforcement, are enhanced to conduct electricity. Electrokinetic geosynthetics have the capability to effect the movement of water in soils by electrokinetic means. The papers confirm the potential for the use EKG for reinforced soil and present the results of pullout tests as evidence. Hamir et al. (2001) identified the potential benefits of EKG in reinforced soil to be:

1. Dramatically increasing the rate of dissipation of positive pore pressure in cohesive fill in excess of that which can be achieved using permeable reinforcement alone;
2. Inducing additional consolidation (and associated increase in shear strength) to that obtained by the self-weight of the fill material above; and
3. Dissipating positive pore pressure at the soil/reinforcement interface to a greater degree than with impermeable reinforcement, thereby increasing reinforcement/soil bond along its entire length.

The paper presented herein briefly describes the concept of EKG and presents the design, construction details, and analysis of

---

[1] Lecturer, School of Civil Engineering and Geosciences, Univ. of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU, U.K.

[2] Emeritus Professor, School of Civil Engineering and Geosciences, Univ. of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU, U.K.

[3] Engineer, GEOCISA, C/Los Llanos de Jerez 10 y 12, 28820 Coslada, Madrid, Spain.

Note. Discussion open until November 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 18, 2004; approved on October 25, 2004. This paper is part of the ***International Journal of Geomechanics***, Vol. 5, No. 2, June 1, 2005. ©ASCE, ISSN 1532-3641/2005/2-138–146/$25.00.

the first full scale wall built using electrokinetic geosynthetic technology.

Electrokinetic Geosynthetics

The ability of electrokinetic phenomena to transport water, charged particles and free ions through fine-grained, low hydraulic permeability materials has been well established. When a direct electrical potential difference is applied across a wet soil mass, ion migration takes place. The positive ions (cations) are attracted to the cathode and repelled from the anode. As the ions migrate they drag with them their water of hydration and exert a viscous drag upon the free pore fluid around them. The process is called electroosmosis and causes a net flow of water toward the cathode described by

$$q_A = k_e i_e A$$

or

$$\frac{Q}{t} = k_e \frac{V}{L} A \tag{1}$$

where Q = quantity of water in cm^3 transported through an area A (cm^2) under an applied voltage gradient V/L (volts/cm) in time t (seconds) in a soil with an electroosmotic permeability of k_e (cm/s per V/cm). The value of k_e is on the order of $k_e = 5 \times 10^{-5}$ cm/s per V/cm (Casagrande 1952) for most soils. This is up to 4 orders of magnitude higher than the hydraulic permeability of clay soils.

Despite this, the use of electrokinetics in soil improvement has been limited. This has been due primarily to difficulties with electrode corrosion, physical removal of water from the system, and the inability to effect polarity reversal.

Geosynthetics are primarily polymer based and are used in conjunction with earth materials to provide drainage, separation, filtration, reinforcement and to act a impermeable membranes. The EKG technology provides an additional electrokinetic function to established geosynthetic uses. Electrokinetic geosynthetic materials are formed by incorporating conductive elements within or associated with a standard geosynthetic material. Alternatively the geosynthetic material can be formed of conducting polymer. The EKG used to construct the reinformed soil wall was formed as a linear reinforced mesh and comprised stainless steel filaments coated and cross-linked with an electrically conducting polymer. This design has overcome the problem of electrode corrosion. Electrolysis of water at the electrodes produces acidic conditions at the anode causing rapid corrosion of the historically metallic electrode. By encasing the metallic filaments in a relatively inert polymer, electrode corrosion is effectively eliminated. By forming the electrode as a geosynthetic, EKG overcomes the problem of removing water by utilizing the drainage function of geosynthetics with the additional advantages of exploiting geosynthetics' reinforcing characteristics and their ability to take on a wide variety of shapes and forms to suit different applications. By making electrodes identical, polarity reversal (critical in dewatering slurries) can be easily achieved without compromising either the drainage function or electrical efficiency.

Table 1. Soil Parameters for Fill Material for Wall

Parameter	Cohesive fill		
LL (%)	60		
PL (%)	35		
PSD (D_{10}, D_{50}) (mm)	$<$0.002,003		
Gs	2.61		
Water content (%)	32	35	41
c_u (kPa) (remolded)	89	49	24
Peak ϕ', c' (remolded)	21°,7.6 kPa	23°,1.3 kPa	22°,6.6 kPa
Residual ϕ', c' (remolded)	20°,5.5 kPa	18°, 7.6 kPa	19°,6.3 kPa
Peak ϕ', c' (undisturbed)	23°,10.5 kPa		
Residual ϕ', c' (undisturbed)	12°,7.8 kPa		
σ (Si/m)	0.6[a]		
EO cell (%) improvement	61%		

[a] This value was obtained using the water available on site.

Electrokinetic Geosynthetic Reinforced Wall

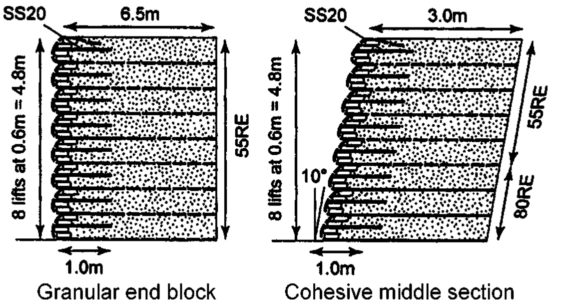
The aim of the wall was to demonstrate, by means of a full scale trial, that electrokinetic phenomena could be applied through the use of EKGs to construct a reinforced soil wall, using an extremely wet overconsolidated cohesive fill, that under normal circumstances could not be built. The trial demonstrated the synergy between electrokinetic phenomena and reinforced cohesive soil through the use of electrokinetic geosynthetics.

The properties of the fill used to construct the wall are presented in Table 1. The undrained shear strength of remolded samples was determined in accordance with *B.S. 1377*: *Part 7* (BSI 1990). Peak and residual shear strength parameters were determined using a shear box test in accordance with *B.S. 1377*: *Part 8* (BSI 1990). Conductivity was determined using the disk electrode method (*B.S. 1377: Part 3*). All remolded samples were prepared using a consolidometer. The results show that there was some variability between the properties, even of the laboratory prepared samples, and that there was some structure to the in situ soil. Both these factors need to be borne in mind when considering the results of the field experiment.

The data relating to electro-osmotic (EO) improvement presented in Table 1 was obtained using the electro-osmotic cell developed by Hamir (1997), with the percentage improvement being taken as the increase in water removed from the sample in the EO cell above that removed in a control cell (no voltage).

Design Philosophy

The design of reinforced soil structures is usually based upon design codes which do not permit the use of cohesive fill and it was not possible to analyze the structure for stability in the short term using established procedures. Therefore, cohesive reinforced soil design methods were developed. These relied upon the geometry of the reinforcement layout being known before the analysis was undertaken. Hence, the stability analysis of the wall was carried out in the long term to ascertain the reinforcement layout (using critical state shear strength parameters for the soil). This layout was then checked for short-term stability. This was achieved using four different analytical methods: critical height, Coulomb, discrete theory, and composite theory. All were used to determine the minimum required undrained shear strength for the clay fill to maintain short-term stability.



Granular end block   Cohesive middle section

Fig. 1. Long-term designs produced for reinforced wall

The water content required to achieve this strength was derived from the water content—undrained shear strength curve for the fill material ascertained from laboratory testing. The difference between the as-placed water content and the water content corresponding to the required strength was used to calculate the volume of water that needed to be removed from each lift of clay fill during construction.

The treatment time required to remove this volume of water was then determined for an array of electrode configurations, based on a linear voltage gradient and fixed soil parameters. This was followed by a more complex analysis using finite difference and resistance path techniques to establish a more realistic voltage gradient. Variations in the value of k_e, using both an empirical model, and a graphical interpretation of the actual variation of k_e (measured in the laboratory) were also considered. The results of these analyses yielded estimated treatment times and estimated power demands drawn by the installation.

Brief descriptions of the results of the short- and long-term designs of the wall are provided below. However, this paper concentrates on the electroosmotic design. Further details of both methodologies may be found in Pugh (2002).

Long- and Short-Term Design

The wall was designed for long-term stability using effective stress parameters for the laminated clay, established from laboratory testing, using an established reinforced soil wall design package *Winwall 6.14* (Netlon Ltd. 1998). A parametric study was conducted for a 4.8 m high, vertically faced wall to assess what variation took place in the reinforcement layout with changes in the effective stress parameters. It was found that a slightly conservative design could be achieved with a fill shear strength of $\phi'=15$, $c'=0$, using secondary reinforcement placed at 600 mm spacing between the main reinforcement. The bottom three layers of reinforcement were formed using 80 kN/m (80RE) reinforcement, the top layers required 55 kN/m (55RE) material, and the secondary reinforcement was 20 kN/m (SS20) material. The ends of the wall were supported by two reinforced soil end blocks constructed using good quality cohesionless fill. The layout of the wall and the supporting end blocks are shown in Fig. 1. The stability of the wall in the short term was based upon the development of cohesion in the clay fill by electroosmosis.

Four different methodologies were developed for the short-term undrained analysis of the reinforced clay wall:

1. Critical height: based on the analysis method proposed by Terzaghi and Peck (1967) for calculating critical vertical cut heights (H_c) in cohesive soil of bulk unit weight (γ) and undrained shear strength (c_u). This method did not consider the contribution of the reinforcement.
2. Coulomb: a more sophisticated undrained analysis, based upon a continuation of the work presented by Ingold, which was based upon Coulomb (1776). The analysis assumed a failure through the reinforced slope at an inclination of $45° + \phi'/2$. For comparison a failure plane inclined at 45° (i.e., $\phi'=0=\phi_u$) was also analyzed.
3. Discrete: considered the undrained shear strength of the clay required to resist the pullout of discrete reinforcing elements and included the influence of the reinforcement.
4. Composite: considered the undrained shear strength of the clay-reinforcement composite system.

The results from the different short-term analytical methods are presented in Table 2.

Table 2. Minimum Undrained Shear Strength Required for Short Term Determined Using Different Analysis Methods

		Inclination of failure plane to vertical	
	Analysis method	$\theta=45°$	$\theta=45°+\phi'/2$
No contribution from reinforcement	Critical height	$c_u=21.6$ kPa	
	Coulomb	$c_u=21.6$ kPa	$c_u=20.9$ kPa
Contribution from reinforcement	Discrete	$c_u=9.6$ kPa	$c_u=8.1$ kPa
	Composite	$c_u=6.2$ kPa	$c_u=6.0$ kPa

The significance of these results to the design of the wall was considered to be:

1. An undrained shear strength of the cohesive fill of the order of 6 kPa would be stable but the strains required to achieve equilibrium could be excessive.
2. An undrained shear strength of the cohesive fill in excess of 10 kPa would be stable as a composite system with both the reinforcement and shear strength of the clay being utilized to maintain the stability of the system.
3. An undrained shear strength of the cohesive fill in excess of 22 kPa would be sufficiently high, such that the system would be stable with little if any load being taken by the reinforcement.

In conclusion it was considered that if the undrained shear strength of the cohesive fill could be increased to 10–20 kPa, then the wall would remain stable in the short term and allow construction to be completed to the design height.

Electroosmotic Design

The long- and short-term designs of the wall established that an undrained shear strength (c_u) of between 10 and 20 kPa was required from the clay to ensure the stability of the wall.

The purpose of the electroosmotic design was to establish the following variables:

- The voltage and current to be drawn; and
- The length of treatment time required to improve the shear strength of the clay fill to a maximum of 20 kPa.

In order to assess these variables a design method was developed based upon the quantity of water that needed to be removed from the soil to achieve the desired increase in undrained shear strength. The method is similar to that suggested by Bjerrum et al. (1967).

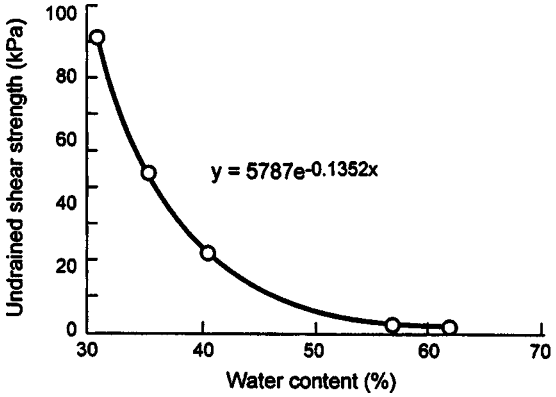


Fig. 2. Relationship between c_u and water content for remolded fill

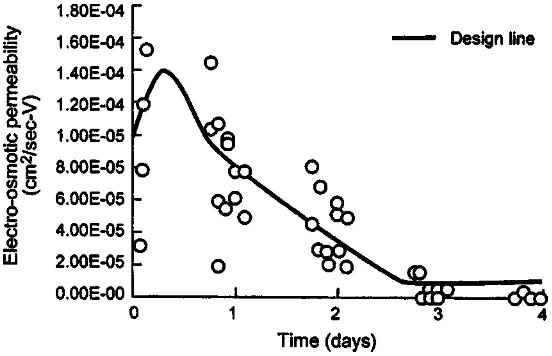


Fig. 3. Graphical interpretation of k_e against time for design purposes

Preliminary Electroosmotic Design

Using the soil parameters obtained from the laboratory testing presented in Table 1, a relationship was established relating the undrained shear strength of the clay to the water content for remolded samples (Fig. 2). The use of remolded samples was justified because the clay for the wall was remolded before being placed. Assuming that the clay was placed in a very fluid state with an undrained shear strength of approximately 1–1.5 kPa with an associated water content on the order of 75–65%, as shown in Fig. 2, and knowing that the required shear strength of 20 kPa is associated with a water content of 42% it was possible to establish that the required reduction in water through electroosmosis was approximately 33–23%.

The volume of soil to be treated in each 600 mm lift of the 24 m long, 3 m wide wall was 43.2 m^3. For a 23 and 33% reduction in water content from 65 to 42% and 75 to 42% the volume of water that needed to be removed was 9.7 and 12.7 m^3, respectively. If the value of k_e is assumed to be that suggested by Casagrande (1952), $k_e = 5 \times 10^{-5}$ cm/s per V/cm, and V/L is established by simply dividing the applied voltage by the distance between the anode and cathode assuming point electrodes, then a preliminary treatment time of between 3.7 and 9.0 days is obtained for each 600 mm lift of clay (Table 3). It is also worth noting that if 9.7 and 12.7 m^3 of water are removed from the soil mass then the change in volume associated with the removal of this volume of water would cause a surface settlement of approximately 130–175 mm over the whole surface area.

From Table 3 it can be seen that by varying the electrode spacing and, hence the voltage gradient, the theoretical treatment time could be altered. The treatment times calculated in this manner are simplifications as they do not take into account the desiccation of the soil with time nor do they take into account electrochemical changes that take place within the soil mass during electroosmosis treatment. As a result the times calculated in this way were considered as lower bound values.

Advanced Electroosmotic Design

The preliminary design can be enhanced by refining the input parameters in Eq. (1)

1. Electroosmotic permeability (k_e)—the value of k_e applicable to the soil in question at the relevant voltage gradient was established from laboratory testing and the variation with time may be taken into account; and
2. The voltage gradient (V/L) can be established more realistically using Laplace's equation and a finite difference analysis, and taking into account the geometry of the electrode layout.

Refinement of Electroosmotic Permeability (k_e)

Mitchell (1993) states that the value of the parameter k_e is generally in the range of 1×10^{-5} to 1×10^{-4} cm^2/s V (cm/s per V/m) and Casagrande (1952) states the range as being 2×10^{-5} to 5×10^{-5} cm^2/s V. However, as treatment progresses and electrochemical reactions take place desiccation of the soil occurs due to the removal of water by the electroosmosis process. As a result, the quantity of water moved per unit of voltage decreases. The significance of this variation in k_e is that initially the flow of water achieved by electroosmosis increases to a maximum within the first 12 h of treatment followed by a rapid decrease in the volume of water moved per unit time, followed in turn by a lower steady-state flow.

To model this phenomena, for practical application to the wall, a constitutive model for the variation of k_e with time was developed under different voltage gradients, (Fig. 3).

Table 3. Results of Simplistic Electroosmosis Analysis

Horizontal electrode spacing (m)	Assumed voltage gradient at 30 V (V/cm)	Assumed k_e (cm^2/s V)	Water content reduction required (%)	Treatment time (days)
0.4	0.83	5×10^{-5}	23–33	3.7–4.9
0.8	0.60	5×10^{-5}	23–33	5.2–6.8
1.2	0.45	5×10^{-5}	23–33	6.9–9.0
Whole wall	0.63	5×10^{-5}	23–33	4.9–6.5

Table 4. Summary of Estimated Treatment Times Using Different Voltage Gradients and k_e Variations for 23–33% Reductions in Water Content

Electrode spacing (m)	Treatment time @30 V for 23–33% w_c reduction (days)			
	Simplistic linear voltage variation		Finite difference voltage variation	
	Assumed k_e	Measured k_e	Assumed k_e	Measured k_e
0.4	3.7–4.9	3.1–9.0	6.5–8.5	16.0–26.0
0.8	5.2–6.8	9.5–17.5	9.4–12.3	30.7–45.2
1.2	6.9–9.0	18.2–28.8	12.4–16.3	45.8–50+

The calculation of treatment times based upon the graphical interpretation presented in Fig. 3 was undertaken by digitizing the curve and using a spreadsheet to calculate the volume of water that flows in a time increment of 0.1 days. In this way, when the cumulative flow volume is equal to the volume of water required to be removed, the corresponding cumulative treatment time can be established.

Refinement of Voltage Gradient Parameter (V/L)

It was assumed in the simplistic design that the voltage gradient could be obtained by dividing the applied voltage by the spacing between anodes and cathodes. This is a simplification of what occurs in reality. The true voltage distribution obtained by the application of a potential difference by point electrodes is given by Laplace's equation (Stroud 1990; and Young and Freedman 1996). Laplace's equation was used in a conventional spreadsheet program to provide a more realistic distribution of the potential electrical field as demonstrated by Williams et al. (1993).

In practice, the voltage distribution will change with time as a result of the variation of the resistance of different zones of the soil due to desiccation, electrochemical changes within the soil mass, and closure of the electrode spacing due to settlement of the fill. This has been observed both in the field and in the laboratory by several researchers (Bjerrum et al. 1967; Mitchell and Wan 1977; Lo et al. 1991a,b). However, to model the complexity that this continual variation of resistance with time would introduce was not considered viable for design purposes.

The treatment times predicted by the simplistic and refined analyses are shown in Table 4.

The relationship between the water content and the undrained shear strength (c_u), together with the variation of electro-osmotic permeability (k_e) obtained from the laboratory testing, provides a means to predict the variation of the undrained shear strength as treatment progressed. Fig. 4 shows the variation of c_u against time for the voltage gradients established from the finite difference analysis and for the two assumed initial water contents.

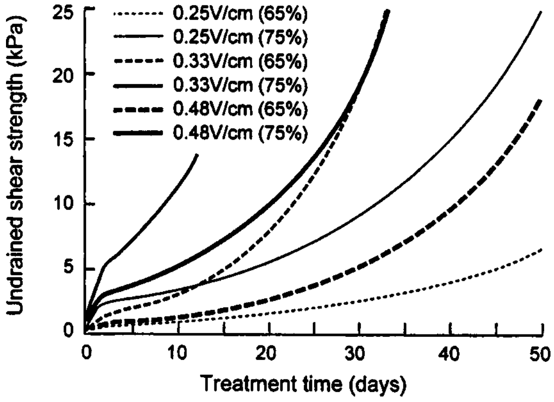


Fig. 4. Variation of c_u against time at different voltage gradients and initial w_c

Fig. 4 shows that the curves, predicting the undrained shear strength, contain a kink at a treatment time of approximately 2.7 days. This kink relates to the change in the electro-osmotic permeability to a constant value, as shown in Fig. 3. Knowledge of the variation of c_u with treatment time is useful, as strength is a parameter that can be measured rapidly in the field by means of a shear vane. In turn this made it possible to confirm that the electro-osmotic treatment was progressing as anticipated.

Inspection of Table 4 reveals that the treatment times predicted using the linear voltage variation are the shortest due to the simplifications used to obtain the voltage gradient. They were thus considered as a lower bound solution for the treatment time. It is important to note that scale effects were not considered in the extrapolation of the laboratory results to the field prediction.

Construction of Wall

The wall was constructed using a wraparound design, utilising sandbags for temporary stability of the front face. The ends of the "cohesive fill" trial section were retained using conventional reinforced soil blocks, constructed before starting the cohesive section. A small additional cohesive trial section was constructed at one end of the wall contemporaneously with the main trial. No electricity was supplied to this zone so that it would act as a control. This area was retained on one side using gabions.

The main trial section was subdivided into three sections each having a horizontal electrode spacing of 1.2, 0.8, and 0.4 m, respectively. Geosynthetic drains were placed midway between the electrodes to provide a drainage path for the excess pore water pressure. The reason for different electrode spacings was to achieve different electric field intensities, thus a variation in ΔV in Eq. (1) could be achieved using a single power source. The electrical potential applied across the electrodes was 30 V dc. This gave initial voltage gradients of 0.45, 0.6, and 0.83 V/cm based upon the anode/cathode spacing.

The wall was constructed using a staged construction technique, such that a single lift of clay fill was constructed and dewatered vertically by electroosmosis applied via horizontally placed electrodes and drains. Once one lift had been successfully treated then the next lift was constructed, and the process repleated until the full height of the wall was achieved, a total of eight lifts. The construction and dewatering processes is shown in Fig. 5.

The electrodes used were EKG consisting of a geonet construction manufactured using a counter-rotating die process. The clay used for the construction was slurrified using a 360° excavator within a lake located at the front of the trial area. Slurrification was achieved by excavating a hole within the clay in the lake and adding water. The mixture was worked with the bucket of the

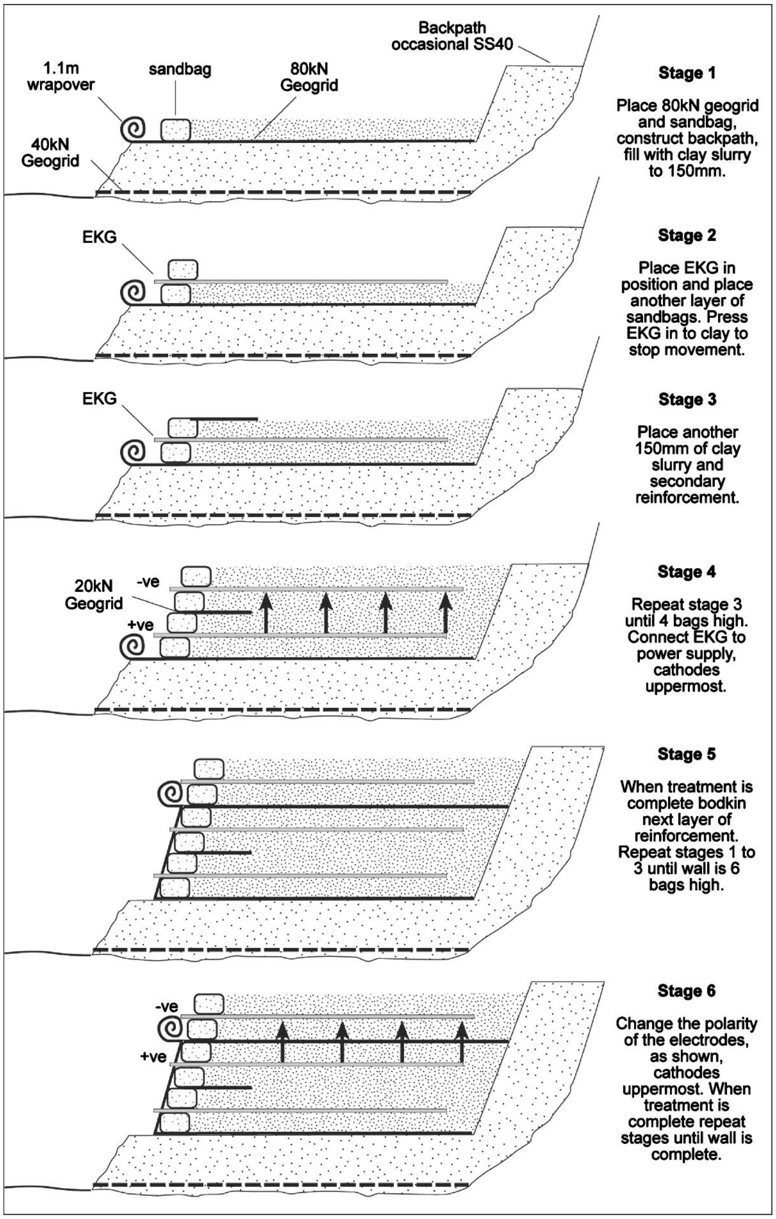


Fig. 5. Construction sequence for cohesive wall

excavator for approximately 1 h until its consistency was that of a fluid slurry. When placed within the wall structure the slurry fill was self-leveling. Laboratory tests on the slurry gave a water content of approximately 75% (approximately liquid limit +20%) which corresponded to a c_u of approximately 1–1.5 kPa, (Fig. 2). During the construction of the first lift the moisture content during placing was slightly lower at approximately 50% with a corresponding c_u of 5 kPa; this was due to a lack of mixing and inexperience of the construction technique.

Monitoring and Analysis of Wall

During the construction of the wall several aspects of the construction were monitored, including fuel consumption, electrical power (voltage and current), undrained shear strength (c_u) of the cohesive fill, and movement of the front face. Pore-water pressures and surface settlements were not measured due to the practical difficulties posed by the construction sequence and the corrosion of metallic instrumentation. The results of current and shear strength measurements are presented below.

Electrical Current

The quantity of current drawn at the prescribed voltage (30 V) was measured using the analog dials located on the transformer/rectifier. The frequency of readings was varied to reflect the rate of change of current drawn, i.e., during the initial powering up of a lift for treatment, readings were taken every 15 min. As the rate of change of current declined the time interval between readings was increased until one reading was taken every hour during the working shift. During initial powering up, the electrodes were connected in groups of five, i.e., 5 anodes and 5 cathodes. In this way it was possible to record the initial current drawn by the different electrode spacing configurations and also allowed any

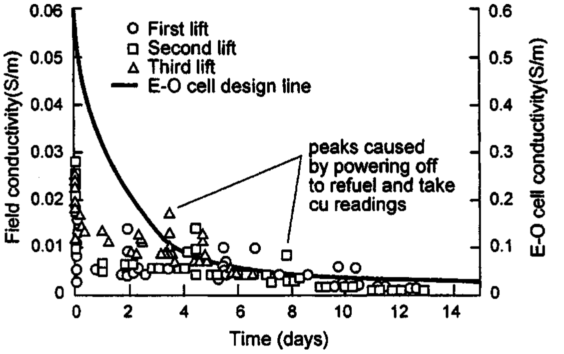


Fig. 6. Variation of electrical conductivity, laboratory, and field

discrepancies in electrical resistance to be identified to a set of five electrode pairs for further investigation. It also enabled a quantification of the difference in resistance of the different electrode spacings used in the trial.

The electrical currents measured in the field could not be compared directly with those obtained from the laboratory testing due to the difference in volume of soil being treated (conductivity is related to the properties of the soil, the electrical contact between the soil and the electrode, the properties of the electrode and the shape of the electric field. Current, and indeed conductance, are additionally related to the distance between the electrodes and the area of electrode–soil contact.) To allow a more direct comparison of the results the current drawn was converted into an overall electrical conductivity (σ) of the system by rearranging Eq. (1)

$$\sigma = \frac{1}{R}\frac{L}{A} \tag{2}$$

where

$$R = \frac{V}{I} = \frac{30\ \text{V}}{I} \tag{3}$$

The results of the electrical conductivity for the wall are presented in Fig. 6 for the different lifts of the wall, together with the design line obtained from laboratory testing.

It was apparent that the actual electrical conductivity measured in the field was approximately ten times less than that obtained from the laboratory electroosmosis cell. This result is logical when the configuration of the two different situations is considered. The electroosmosis cell used plate electrodes and hence the electrical field established was one-dimensional, and theoretically the voltage gradient that occurs within the cell was uniform. In the field construction the voltage was applied to the wall by means of EKG linear strips, which may be considered as point electrodes, thus generating an essentially two-dimensional electrical field, with the effect being more pronounced at greater spacings between electrodes of the same polarity.

In addition, Fig. 6 shows that the electrical conductivity of the fill in the wall underwent a reduction with time of the order of 95% from an initial value of approximately 0.026 to 0.0013 S/m. This compares with the values suggested in the design method.

Undrained Shear Strength

The undrained shear strength of the cohesive fill undergoing electro-osmotic treatment was measured using a Pilson hand shear vane with a $1\frac{1}{4}$ in. (31 mm) vane. The measurements of undrained shear strength were taken at two depths: 0.25 and 0.5 m in each lift to distinguish the variation in shear strength in the fill between the anode and cathode positions. To reduce errors five readings were taken at each location and averaged at each depth, at approximately the same locations along the wall. The undrained shear strength was measured every 2 m along the full 24 m length of the electroosmosis zone and at three different locations in the control zone. Additionally, samples were taken of the soil from the shear vane test locations for laboratory testing to establish their water content.

The interpretation of the field measurements of the undrained shear strength obtained from the hand shear vane and corrected for conversion to field shear strength, was undertaken by superimposing the theoretically calculated shear strength based upon an initial water content and voltage gradient calculated by the finite element analysis. Due to the large variation in the results obtained from the hand shear vane, even within the zones of the same electrode spacing, a zonal average was calculated for each of the electrode spacings used (i.e., 0.4, 0.8, and 1.2 m) and the control zone. This allowed easier interpretation of the results by eliminating the large degree of scatter that was present in the unrefined field results. These results are plotted in Figs. 7 and 8 for the two test depths of 0.25 and 0.5 m. The variation between the 0.25 and the 0.5 m depth readings illustrates the difference in the strength changes with proximity to the anodes or cathodes.

Inspection of Figs. 7 and 8 reveals that the initial undrained shear strength (c_u) demonstrated a large degree of scatter but generally was in the range of $\approx 3-15$ kPa. The higher values were attributable to lumps of harder clay in the slurry due to ineffective mixing. The design line for an initial water content of 65% at a voltage gradient of 0.48 V/cm shows a relatively good correlation with the field measurements of shear strength. Nearly

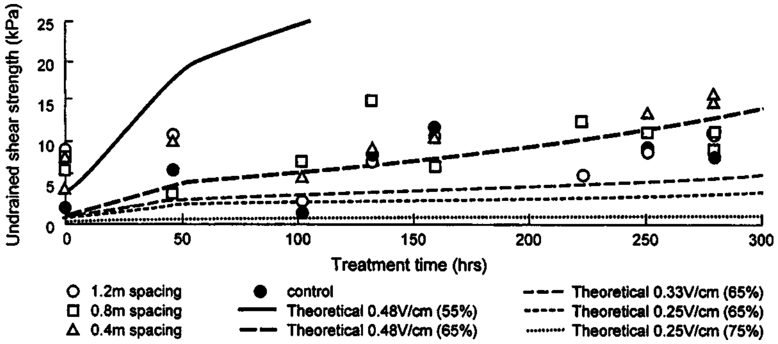


Fig. 7. Theoretical and zonal average results of c_u against treatment time, 0.25 m test depth

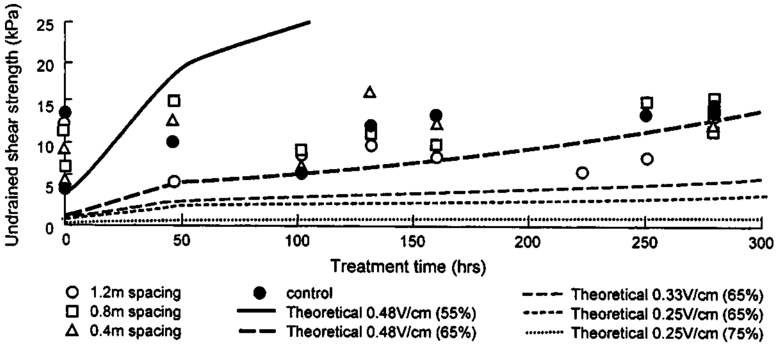


Fig. 8. Theoretical and zonal average results of c_u against treatment time, 0.5 m test depth

all the undrained shear strength results measured in the field fell within realistic ranges defined by the theoretical curves. The field measurements of zonal averages show an obvious improvement with increasing treatment time.

The results obtained at a test depth of 0.25 m are generally lower than those obtained at a test depth of 0.5 m. Consideration of the electrode depths, with the anode at 0.45 m and cathode at 0.15 m depth, respectively, explains these results. The results at a depth of 0.5 m are located immediately below the anode, whereas the results obtained at a depth of 0.25 m are located closer to the cathode.

The control zone also showed an improvement in shear strength with time. This was caused by self-weight consolidation which was aided by the inclusion of drainage paths through the electrodes and filter elements. However, due to the reduced nature of the improvement that took place within the control zone the continued construction of the zone became increasingly more difficult as the height of the construction increased.

The initial undrained shear strength assumed for the theoretical analysis appeared to be critical in the theoretical prediction. This was attributable to two factors:

1. The relationship between c_u and w_c is not linear, but approximately exponential, as shown in Fig. 2, hence a greater increases in c_u occurs for a smaller reduction in w_c at lower water contents.
2. The variation of the electro-osmotic permeability with time is not linear, as demonstrated in Fig. 3, with a significant decrease in k_e taking place after a period of approximately 2 days (48 h). This is reflected in Fig. 4 by the change of slope in the predicted value of c_u that occurred after a treatment time of approximately 50 h.

The combination of these two factors exaggerates the effect of electrokinetic treatment on soils with lower water contents, but also minimizes the effect of treatment on soils with an initial high water content as shown by the curve for 75% initial water content in Fig. 4.

The electrode spacing, and hence the voltage gradient, also had a significant effect on the treatment process as demonstrated by the increased improvement of the 0.4 m electrode spacing zone over the other zones. The theoretical analysis also predicted this as shown in Fig. 4 by the curves of 0.48, 0.33, and 0.25 V/cm corresponding to electrode spacings of 0.4, 0.8, and 1.2 m, respectively, at an initial water content of 65%.

Treatment Time

During construction, the measurement of treatment time could only be measured indirectly by means of the shear strength and by means of the variation of current against generator time. Fig. 6 shows that the conductivity of the fill in the structure had reached its residual value after a period of 10–12 days of generator operation. After this time the efficiency of the installation would be extremely low with the majority of the voltage being dropped across the high resistance zone adjacent to the anode.

Practical Applications

The trial demonstrated the successful use of EKG in the construction of a reinforced wall using a cohesive "slurry" fill. Whilst it is recognized that the properties of the fill used were extreme in the sense that they fell well outside the bounds of what would normally be regarded as fill material, some important principles have been established. It is possible to construct reinforced soil structures using cohesive fill and EKG because drainage is not dependent upon hydraulic permeability. Thus construction may be permitted using very poorly draining material and/or material with a high water content without the risk of generating very high pore water pressures.

With increasing environmental pressures requiring reuse of construction materials on site this may be of significant benefit. There may no longer be the need to import high quality fill (and dispose of poor quality fill) for construction of, for instance, embankments, bunds, or abutments. Repairs to clay slopes, particularly where access is problematic, or where high quality fills are in short supply, may be possible using material found on site.

Additional applications include improvement of waste materials, particularly in cases where water contents are very high, including dredgings and tailings.

Conclusions

On the basis of the results presented herein it may be concluded that the proposed electro-osmotic design method is a valuable predictive tool for estimating the change in undrained shear strength with time during an electro-osmotic treatment process. The accurate input of the initial soil and treatment parameters used in the analysis is critical to its correct function. It is suggested that a sensitivity study is undertaken using the analysis method and an envelope of shear strength/treatment times established for a realistic range of conditions that may exist in the field and that appropriate laboratory testing is used to establish the variation of k_e to be used in the analysis.

The laboratory method for predicting current drawn produces an overestimation by a factor of 10 of that which occurs in practice, this is due to the differences in the shape of the respective electrical fields. It would appear sensible to use this to calculate extreme upper bounds of likely power consumption during any full-scale application.

Although not discussed in detail, the design approach adopted for the initial design of the electrode spacings would appear sensible and offer a pragmatic approach that could be adopted using skills and software available in most design offices.

Lastly, the applications of this technology are numerous, particularly with increasing pressures on the reuse of waste and sustainable construction. "R-EKG wall" could be the next generation of earth structures.

Acknowledgments

The writers would like to thank the Engineering and Physical Sciences Research Council for supporting the work. Skanska Cementation, Tensar International Ltd. CAPITOL, Naue Fasertechnik GmbH, Okasan Livic Co., Ltd. provided funding, materials, construction equipment, and invaluable advice.

Reference

Bjerrum, L., Moum, J., and Eide, G. (1967). "Application of electroosmosis to a foundation problem in a Norwegian quick clay." *Geotechnique*, 17, 214–235.

British Standards Institution (BSI). (1990). "British standard methods of test for soils for civil engineering purposes." *BS 1377*, London.

British Standards Institution (BSI). (1995). "Code of practice for strengthened/reinforced soil and other fills." *BS 8006*, London.

Casagrande, L. (1952). "Electro-osmotic stabilisation of soils." *J. Boston Soc. Civ. Eng.*, 39, 51–83.

Coulomb, C. A. (1776). "Essai sur une application des régeles des maximus et minimus a quelque problémes de statique re'latif à l'architecture." *Memoirs Divers Savants*, Vol. 7, Académie Sciences, Paris.

Hamir, R. B. (1997). "Some aspects and applications of electrically conductive geosynthetic materials." Doctor of Philosophy thesis, Univ. of Newcastle upon Tyne, Newcastle upon Tyne, U.K., 225–225.

Hamir, R. B., Jones, C. J. F. P., and Clarke, B. G. (2001). "Electrically conductive geosynthetics for consolidation and reinforcement." *Geotext. Geomembr.*, 19(8), 455–483.

Jones, C. J. F. P. (1990). "Construction influences on the performance of reinforced soil structures, state-of-the-art review." *Proc., Int. Conf. on Reinforced Soil*, Glasgow, Scotland, 97–116.

Jones, C. J. F. P. (1996). *Earth reinforcement and soil structures*, Thomas Telford, London, 379–379.

Jones, C. J. F. P., Fakher, A., Hamir, R., and Nettleton, I. M. (1996). "Geosynthetic materials with improved reinforcement capabilities." *Proc., Int. Symp. on Earth Reinforcement*, Fukuoka, Kyushu, Japan, 865–883.

Lo, K. Y., Ho, K. S., and Inculet, I. I. (1991a). "Field test of electroosmotic strengthening of soft sensitive clay." *Can. Geotech. J.*, 28, 74–83.

Lo, K. Y., Inculet, I. I., and Ho, K. S. (1991b). "Electroosmotic strengthening of soft sensitive clay." *Can. Geotech. J.*, 28, 62–73.

Mitchell, J. K. (1993). *Fundamentals of soil behaviour*, 2nd Ed., Wiley, New York, 437–437.

Mitchell, J. K., and Wan, T. Y. (1977). "Electro-osmotic consolidation—Its effects on soft soils." *Proc., 9th Int. Conf. on Soil Mechanics and Foundation Engineering*, Tokyo, Vol. 1, Balkema, Rotterdam, The Netherlands, 219–224.

Netlon Ltd. (1998). *Winwall Version 6.14., Reinforced Soil Design Package*, Tensar International, Blackburn, U.K.

Nettleton, I. M., Jones, C. J. F. P., Clarke, B. G., and Hamir, R. (1998). "Electrokinetic geosynthetics and their applications." *Proc., 6th Int. Conf. on Geosynthetics*, Atlanta, Vol. 2, 871–876.

Pugh, R. C. (2002). "The application of electrokinetic geosynthetic materials to uses in the construction industry." PhD thesis, Univ. of Newcastle upon Tyne, Newcastle upon Tyne, U.K.

Stroud, K. A. (1990). *Further engineering mathematics—Programmes and problems*, 2nd Ed., Macmillan Education, London, 1063–1063.

Terzaghi, K., and Peck. (1967). *Soil mechanics in engineering practice*, 2nd Ed., Wiley, New York, 566–566.

Williams, B. P, Smyrell, A. G., and Lewis, P. J. (1993). "Flownet diagrams—The use of finite differences and a spreadsheet to determine potential heads." *Ground Eng.*, 32–38.

Young, H. D., and Freedman, R. A. (1996). *University physics*, 9th Ed., Addison-Wesley, Reading, Mass., 1259–1259.