Electrokinetic strengthening of soft soil

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ABSTRACT: Electrically conductive geosynthetics (EKG) combine electrokinetic phenomena with conventional geosynthetic functions. These "active" geosynthetics can be used in a range of applications including, the strengthening of failing slopes, dewatering waste lagoons and as an alternative to conventional soil consolidation using wick drains and surcharge loading. The electrokinetic phenomenon applicable to soil consolidation and strengthening is electroosmosis. In the case of soil consolidation, electrokinetic treatment can offer technical and economic benefits identified as a major reduction in the time required for consolidation to occur and the elimination of the need for surcharge loading. Due to changes in weather patterns a growing number of previously stable structures and slopes are in danger of collapse or failure. A particular problem relates to embankments and cuttings associated with rail/road networks. Remedial strengthening of these structures can be accomplished by electrokinetic geosynthetics, which not only affect an increase in shear strength of the parent material, but can also provide additional drainage and reinforcement. A Case History shows that the cost of electrokinetic treatment to be less than other remedial methods and also has a significantly reduced carbon footprint.

1 INTRODUCTION

Following the observation of electrokinetic phenomena by Reuss (1809) and the distinction between electrolysis and electroosmosis by Napier (1846), it has been accepted that electroosmosis offers the potential to consolidate and strengthening fine grain soils and wastes. However, until recently the application of electroosmosis in practice has had little success due mainly to limitations of the electrodes. The use of metallic electrodes results in corrosion of the anode, potential contamination of the ground from dissolved salts and the production of gases. The result is poor electrical contact with the soil and an increase in electrical resistance leading to a rapid degradation of the effectiveness of the process and excessive power consumption. The development of electrokinetic geosynthetic materials (EKG) eliminates these problems.

The concept of electrically conductive geosynthetic (EKG) materials was introduced by Jones *et al* (1996). EKG materials are geosynthetics which can be enhanced by electrokinetic techniques for the transport of water and chemical species within fine grained low permeability soils and wastes, which are otherwise difficult or impossible to deal with. The EKG can take the form of a single material which is electrically conductive, or a composite material, in which at least one element is electrically conductive. EKG electrodes produce high electroosmotic performance by the provision of:

- Control of corrosion
- Dense network of electrical soil contact
- Efficient drainage of fluids and gases
- Exploitation of the traditional functions of geosynthetics (e.g. drainage, reinforcement)
- Ability to be produced in 2D or 3D forms.

The development of EKG materials and forms has been described in detail by (Jones *et al* 2008).

This paper provides an explanation of the concept of electrically conductive geosynthetics and how they can be used to improve the strength of soft soils. The use of EKG materials in consolidation is briefly detailed followed by a more in-depth description of electrokinetic strengthening of slopes. Details of cost and the permanency of treatment are provided. The paper concludes with a recent Case History of the strengthening of a failing railway embankment.

2 EKG CONCEPT

In use most geosynthetics play a ***passive*** role, e.g. geomebrane barriers stop the passage of liquids; soil reinforcement provides tensile resistance, but only after an initial strain has occurred; and drains provide a passage for water but do not cause the water to flow towards the drain. New applications for geosynthetics have been identified if they can provide an ***active*** role, initiating biological, chemical or physical change to the matrix in which they are installed as well as providing the established functions. This can be achieved by combining the electrokinetic phenomena of electroosmosis, electrophoresis and associated electrokinetic functions such as electrolysis with the traditional functions of geosynthetics of drainage, filtration, containment and reinforcement to form electokinetic geosynthetics (EKG).

EKG is a platform technology, which combines a wide variety of materials, functions and processes to perform such diverse functions as dewatering, strengthening and conditioning in materials such as soils, sludges, slurries, tailings and composts. Applications have been identified in a range of industrial sectors including water, mining, civil and environmental engineering, food and sport. Table 1 shows the main technical components which form the backbone of EKG technology. These are explained further in Table 2.

Table 1. Functions used in practical applications of EKG

	Function	**Effects**
Electro-kinetic EK	1. Electro osmosis	Water flow Pore pressure change Volume change
	2. Electrophoresis	Particle movement Particle orientation
	3. Ion Migration	Solute movement
	4. Electrolysis of water	Oxygen evolution Hydrogen evolution pH changes
	5. Heating	Joule heating (electrode) Resistive heating (soil)
	6. Oxidation reactions	Soil cementation Reduction in soil plasticity
	7. Reducing reactions	Electro-winning of metal ions Evolution of ammonia
Geosyn-thetics G	1. Drainage	Water flow Gas flow
	2. Reinforcement	Tensile strength In-plane stiffness
	3. Filtration	Barrier to solids entrained in flow
	4. Separation	Strengthening & prevent mixing
	5. Containment	Physical containment of solids
	6. Membrane action	Barrier to flow (containment of fluids)
	7. Sorption	Capture of liquids or dissolved species

Table 2. Key parameters, their effects and practical implications of the main electrokinetic functions of importance in EKG

	Parameter	Effect
ELECTRO-OSMOSIS	Water flow rate, $Q = k_e.V/L.A$	Drainage & water content
	Pore water pressure $u = (k_e/ k_h).\ V/L$	Consolidation or Decompaction
	pH $\Delta pH = f.(I/A)$	Acid /alkali changes
	$[O_2]$, $[H_2]$ $\Delta\ [O_2]$, $[H_2] = f.(I/A)$	Oxygenation i.e. Redox potential
ELECTRO-KINETIC HARDENING	f pH. CEC. electrode composition	Stiffening of soil / waste
JOULE HEATING	$f = I^2R$, SHC & conductivity of material	Heat generation

Where: K_e = Coefficient of electro osmotic permeability (m^2/sV), K_h = Coefficient of hydraulic conductivity (m/s), σ = Electrical conductivity of sludge/waste mixture, w = Water content, V/L = Potential gradient (V/m), A = Area (m^2), I = Current (A), Ts = Thermal conductivity of sludge/waste mixture, $[O_2]$, $[H_2]$ = Concentration of aqueous and gaseous O_2 and H_2, CEC = Cation exchange capacity, f = function.

2.1 *Electrokinetic Geosynthetics*

Traditional geosynthetics and industrial textiles are used in the civil, mining, environmental and waste engineering industries to carry out a range of functions which include drainage, reinforcement, filtration, separation, containment, encapsulation and sorption. All of these functions, in one way or another are influenced or limited by the rate at which water is able to flow through the materials with which the geosynthetics are being used to improve or treat.

Water normally flows in response to a difference in pressure identified as hydraulic head. The rate of water flow is determined by the permeability of the material and is directly related to grain size such that coarse grained materials such as sands and gravels have a high hydraulic permeability, whereas fine grained materials such as silts, clays or sludges have a low permeability. The practical consequence of this is that it is usually very difficult to move water in, out or through materials such as silts and clays. Engineers from many backgrounds need to control water content or water movement in these materials in order to influence characteristics such as strength, volume and content of the water phase such as contaminants, cementitious elements or bacteria.

Electrokinetics refers to the relationship between electrical potential and the movement of water and charged particles. Effects directly related to the application of a voltage via electrodes include; heating, electrolysis of water, and other electrochemical processes. Under a DC voltage water flows by electroosmosis from the anode (+ve) to the cathode (-ve), Figure 1.

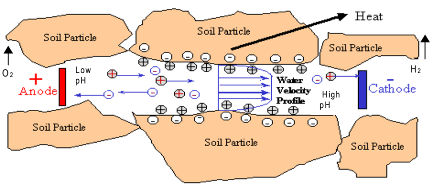

Figure 1. Conceptual representation of electroosmosis in soil

Removal of water from the cathode causes changes in the material such as an increase in strength (useful in ground engineering) and a reduction in volume (useful in waste engineering). Additional processes include (Table 2):

- Movement of positive and negative ions (useful in soil conditioning or decontamination)
- Movement of particles in the water (e.g. removal of pathogenic bacteria)
- Production of oxygen at the anode (useful for composting and sports turf aeration)
- Production of heat (useful for composting and frost prevention in sports turf)
- Evolution of ammonia at the cathode (useful in sewage treatment to reduce total nitrogen)
- Changes in pH (useful in regulating the acidity of growing media for sports turfs)
- Oxygenation reactions or electrochemical hardening of soils (useful in slope stabilisation).

Electroosmosis is the most useful of the electrokinetic processes activated with EKG because it holds the potential to overcome the limitations of very slow and in some cases effectively zero hydraulic flow in fine grained, low permeability materials such as silts and clays. Figure 2 shows that, wheras hydraulic permeability is related to grain size, electroosmotic permeability is effectively independent of grain size. This means that electroosmosis can result in flow rates 100 to 10,000 times greater than hydraulic flow in fine grained materials. Since water is directly related to strength, volume and the movement of contaminants or nutrients, the ability to effect water movement is highly valuable. It is important to recognize that Figure 2 is schematic and that electroosmotic flow is a function of a number of factors identified below.

The first full scale EK drain/reinforcement for use in dewatering/consolidation was formed as an electrically conductive geonet core surrounded by a thermally bonded non woven filter fabric. The geosynthetic material used in the product was made conductive by the addition of carbon black powder to the conventional polymers. Monofilament wires were located at the centre of alternate ribs to act as current distribution stringers. The wires were of much higher electrical conductivity than the conductive polymer and this arrangement provided a more efficient distribution of current through the length of the EKG, Nettleton *et al* (1998). The efficiency of the EK drain was studied by Hamir *et al* (2001) who found it to compare well with copper electrodes. This form of electrode has been used in a wide range of laboratory studies in Australia, South Africa and the United Kingdom. The product has been superseded by more advanced forms of EKG more suitable for practical applications, Jones *et al* (2008)

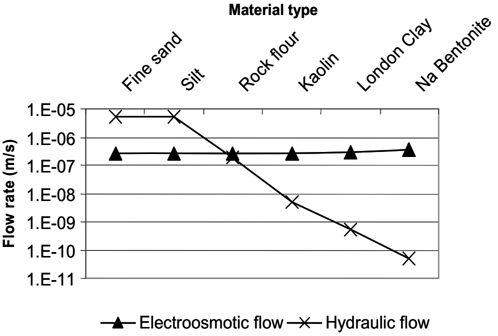

Figure 2. Comparison of hydraulic and electrokinetic flow rates

3 ELECTROOSMOTIC CONSOLIDATION

The drivers for the use of EKG materials and systems to consolidate difficult soils/materials are to resolve construction problems, accelerate construction or to provide a more economical solution to foundation design. Electrokinetic strengthening of soil has been undertaken by a number of practitioners including: Casagrande (1949, 1952, 1983), Fetzer (1967), Bjerrum *et al* (1967), Chappell and Burton (1975), Lo *et a*l (1991a and b, 2000). The technique was also used for the dewatering and consolidation of mine tailings by; Sprute and Kelsh (1975), Lockhart (1983), Shang (1997), Fourie *et al* (2004), Fourie *et al* (2007) and Lamont-Black *et al* (2007). The consolidation of waste lagoons by electrokinetic geosynthetics has been described by Glendinning *et al* (2005), Lamont-Black *et al* (2005) and Jones *et al* (2006). The problem of the consolidation of peat may also be possible with the use of EKG materials, Kulathilaka *et al* (2004). Cementation agents and bio remediation agents have been introduced into the soil through the technique by; (Mohomadelhassan and Shang 2003, Shang *et al* (2004).

Conventional consolidation uses prefabricated vertical drains (PVD) and surcharge loading. Consolidation is a function of hydraulic flow and can be expressed by Darcy's law:

$$Q = K_h \, i_h \, A \qquad (1)$$

Where Kh is the hydraulic conductivity, ih is the hydraulic permeability produced by the surcharge loading and A is the area.

Electroosmotic consolidation can be expressed by a similar equation, Table 2:

$$Q = K_e \, i_e \, A \qquad (2)$$

Where K_e is the coefficient of electroosmotic permeability i_e is the potential gradient used in place of surcharge loading and A is the area.

In the case of fine grained soils the effectiveness of electroosmotic consolidation compared with conventional hydraulic consolidation is illustrated in Figure 2.

3.1 *Concept of Electroosmotic Consolidation*

The concept of electroosmotic consolidation of a low impermeable soil mass is illustrated in Figure 3. The application of an electrical potential difference to an impermeable soil with the appropriate drainage conditions (usually anode closed and cathode open or closed) generates negative pore water pressures within the soil mass;

$$u = K_e \gamma_w V / K_h \qquad (3)$$

where K_e is electroosmotic permeability, K_h is hydraulic conductivity, and V is voltage. The generation of negative porewater pressures (u) causes an increase in the effective stress (σ') within the clay with no change in total stress (σ):

$$\sigma' = \sigma - u \qquad (4)$$

As there is an increase in effective stress the soil particles pack together more tightly resulting in consolidation. For the 1-D case the increase in effective stress is equivalent to an equivalent surface loading which would generate the same increase in effective stress and hence the same settlement.

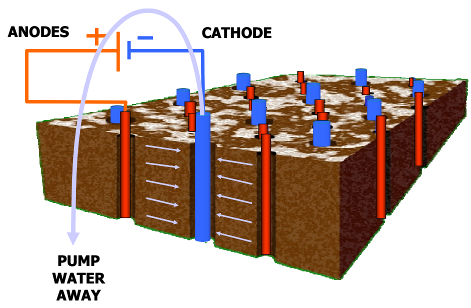

Figure 3 Concept of electroosmotic consolidation

The consolidation settlement caused by electro-osmosis is assumed to continue until the hydraulic force that drives water back towards the anode exactly balances the electroosmotic force driving water towards the cathode. The amount of consolidation that will take place depends upon the soil compressibility as well as the change in effective stress. Electroosmosis is of little use in over consolidated clay unless the increase in effective stress is large enough to bring the soil back onto the virgin compression line.

It has been shown that the minimum negative porewater pressure generated by electroosmosis is limited to approximately –100kPa and the magnitude and distribution of settlement can be obtained based upon conventional consolidation theory.

3.2 *Combined electroosmotic consolidation and surcharging.*

Electroosmosis may be combined with conventional surcharging where electroosmosis is used to induce an additional effective consolidation pressure to accelerate the dissipation of positive pressures. After the positive porewater pressures induced by the surcharge loading have been dissipated, electro-osmosis continues to produce negative porewater pressures, causing further consolidation. Hamir *et al* (2001) have presented experimental evidence confirming these findings.

3.3 *Analysis of Electrokinetic consolidation*

The analysis of electoosmotic consolidation requires the following steps:

- Determine the acceptability of the soil for electroosmotic treatment
- Determine the electroosmotic permeability
- Determine the soil resistivity
- Select electrode configuration
- Determine the electrode layout
- Estimate the current demand

3.4 *Acceptability criteria*

Acceptability criteria of soils for electroosmotic treatment have been developed based upon standard and non-standard soil mechanics tests, Pugh (2002). The relevance of different tests is shown in Table 3.

Table 3. Usefulness of soil tests for assessing acceptability for electro-osmosis (After Pugh 2002)

Test	Use	Acceptability
Atterberg limits	✓✓✓	5 – 30% P.I.
Water content	✓✓✓	0.6 – 1.0 L.I.
PSD – sieve	✓✓✓✓	
Particle density	✓	Not applicable
Organic content	✓✓	Up to organic
Consolidation	✓✓✓	mv, 0.3–1.5MPa
Disk Electrode	✓✓✓	0.05–0.005S/m
Permeability	✓✓✓	<10-8 m/s
Undrained shear	✓✓	<55kPa
Drained shear	✓	$\phi' < 30°$
E-O cell	✓✓✓✓	Not applicable
E-O box	✓✓✓✓	Not applicable

✓✓✓✓ Excellent ✓✓✓ Good
✓✓ Reasonable ✓Poor

3.5 *Electroosmotic permeability*

The electroosmotic permeability of the soil is best determined in an electroosmotic cell of the form described by Hamir (1997).

3.6 *Electrical resistivity*

The electrical resistivity (ρ) of the soil may be determined in accordance with BS1377: Part 3:1990 §10 (BSI 1990). The disk electrode method is the most appropriate. Electrical resistivity may be related to conductivity (σ) by:

$$\sigma = 1/\rho \qquad (5)$$

The range of acceptable and economic values of electrical conductivities (σ) has been found to be in the range of 0.05S/m – 0.005S/m. Values in excess of this range do not indicate that the soil is not susceptible to treatment by electro-osmosis, but that the electroosmosis installation will draw a high current and may not be economic.

3.7 *Electrode configuration*

The most appropriate electrode configuration for electroosmotic consolidation has been found to be a composite prefabricated vertical drain (e-PVD), consisting of a solid porous drainage core surrounded by a geotextile filter fabric and with a plurality of conducting elements outside the filter in direct contact with the soil.

3.8 *Installation and layout of electrodes*

The electrodes can be installed by lance or in predrilled holes. The ideal layout has been found to use a hexagonal arrangement for the anodes with a central cathode. This layout produces an optimum electric field and reduces the number of drains required, Figure 4.

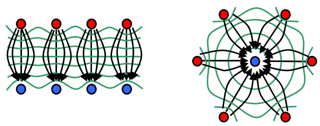

Figure 4. Flow paths for rectangular array (left) and hexagonal array (right).

3.6 *Estimation of current demand*

Estimation of current demand is dependent on a number of variables and is site specific. An indication of current demand can be made using:

$$I_t = ncs\sigma V / L \qquad (6)$$

Where: I_t is total current required for installation, n is number of electrode pairs; c is efficiency factor (2 anodes/cathode ≈ 0.8-0.9); s is embedded surface area of electrode (cm^2); σ is electrical conductivity of soil being treated S/cm; V is voltage; L is distance between anodes to cathodes (cm).

The prediction of the electrical power drawn by the field installation is a function of the variation of the electrical conductivity of the soil with time and the variability of the electrode-soil interface resistance. The extrapolation of the soil conductivity determined using disk electrodes in the laboratory to the full-scale structure using discrete EKG electrodes can lead to discrepancy. As a result the prediction of the current drawn using a simple 1–D resistive block model significantly overestimates the current drawn by a field installation. Comparison of laboratory and fieldwork suggests that a reduction factor of up to 0.1 should be employed (Pugh 2002), i.e.:

$$\sigma_{field} = 0.1\sigma_{e-o\,cell} \tag{7}$$

3.9 *Case studies of Electrokinetic consolidation*

A Case Study of the consolidation/dewatering of lagooned sludge has been provided by Jones *et al* (2006). In addition, Chew *et al* (2004) have reported a field trial of electroosmotic consolidation of Singapore marine clay using EK drains. The objective of the trial was to consolidate the clay and improve the engineering properties. Before embarking on the field study, laboratory tests were conducted on remoulded clay samples. Electro osmotic consolidation was reported to have caused: a decrease in the compression index C_c, coefficient of secondary consolidation, and an increase in C_v, together with a substantial increase in shear strength. The test site consisted of an 18.7 m thick layer of recently placed sand fill overlying an 8 m thick layer of soft marine clay which in turn was underlain by stiff clay and sedimentary rock. It is reported that the EK drains produced a noticeable increase in shear strength in a period of 13 days. Similar strength improvement using conventional drains alone was calculated to take 130 days. The energy cost of treatment was reported to be 1.8kWh/m^3.

4 STENGTHENING OF SLOPES

Failure of cuttings and slopes are caused by three main factors; the development over time of residual strength soil parameters, the fairly recent phenomena of climate change or inundation of water often resulting from burst or leaking water mains. In addition, seismic events can cause liquefaction of the materials forming tailings dams/impoundments. Traditional methods for the repair of failing slopes have included the provision of additional drainage, replacing the fill with high quality material, slackening the slope by the provision of dwarf walls or gabions at the toe (toe weighting), soil nailing, the provision of shear piles or the acquisition of additional land, although the latter is seldom possible. Soil nailing should not be used below the water table and replacing the failed material is expensive with a high carbon foot print. In-situ strengthening is difficult by conventional means and may not be possible at all in some conditions.

The primary objective in the stabilization or maintenance of slopes is to identify potential failing slopes and to return them to full stability before failure occurs. As the failures are predominantly caused by the development of residual shear strength conditions or uncontrolled pore water pressures, an ideal remedial method would be to effect a reduction in pore water pressures and an increase in the shear strength of the material forming the slope/impoundment. This can be achieved by electroosmosis. Electroosmosis can be used, either to aid construction of remedial works or preferably as a means to effect permanent improvement. A major advantage of the electroosmotic process is that it can be installed quickly and with the use of limited equipment. Treatment is rapid and the strengthening can be permanent. The concept of electrokinetic strengthening of a slope is shown in Figure 5. Electroosmotic dewatering of a slope results in a reduction in pore water pressure and an increase in the effective shear strength of the soil, thereby, reducing the risk of a slip plane developing.

Electrokinetic treatment provides benefits identified as:

- immediate effects
- long-term strenghtening measures.

4.1 *Concept of EKG strengthening*

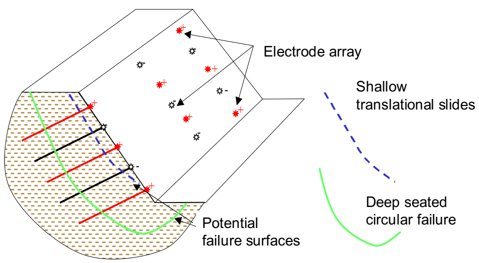

Figure 5 Electrokinetic strengthening of slopes

The orientation of the electrodes is selected to intercept any potential failure plane. Electoosmotic dewatering of the slope results in an increase in the shear strength of the soil, reducing the risk of a slip plane developing. In addition, the electrodes can be formed to act as reinforcement once the electrokinetic treatment is complete. A benefit of dewatering using EKG materials is a major improvement in the bond between the EK reinforcement and the soil, (Hamir *et al* 2001).

4.2 *Immediate effects – pore water pressure reduction*

The immediate effect of the application of an electrokinetic force is a reduction of pore water pressure identified by;

$$u = - K_e/K_h .\ g_w .\ V \qquad (8)$$

Where K_e, K_h, g_w and V have been defined above.

During soil treatment, electroosmotic flow is independent of hydraulic permeability and the degree of negative pore water pressure or suction that builds up is proportional to the ratio of the coefficients of electroosmotic and hydraulic permeability. Therefore, electroosmosis is most effective in fine-grained soils such as clays and silts similar to thickened tailings. By adjusting the parameters of electrode spacing and voltage control, different factors can take priority. For example, if treatment time is critical then the use of close electrode spacing is appropriate. On the other hand if cost is the main driver a wider spacing of electrodes can be used to reduce the number of electrodes and spread the treatment out over a longer duration.

4.3 *Immediate effects – increase in shear strength*

Application of an electrical current between the electrodes results in a flow of water towards the cathode;

$$Q = K_e.V/L.\ A \qquad (9)$$

In many slope materials there is a direct link between shear strength and water content and a small reduction in water content results in a significant increase in shear strength, Figure 6.

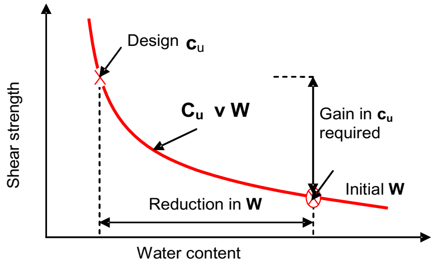

Figure 6 Relationship between shear strength and water content

When the material being dewatered is normally consolidated clay the result is to produce consolidation. Electro-osmosis is of little use in over consolidated clay unless the increase in effective stress is large enough to bring the soil back onto the virgin compression line. With these materials an increase in strength may be caused from chemical effects such as cementing. The increase in shear strength by electrokinetic dewatering has been used as the basic design criteria for the strengthening of clay railway embankments by Casagrande (1952) and the construction of steep/vertical structures formed from very weak materials, Glendinning *et al* (2005).

4.4 *Long-term benefits – reinforcement*

By using steel reinforcing soil nails as the anodes the embankment can be strengthened in the long term. The bond between the nail and the soil is a function of the shear strength of the soil and accordingly is enhanced by the electro osmotic treatment, Hamir *et al* (2001). In addition the increase in soil/nail bond is permanent, Milligan (1994). Slope stabilization with EKG nails can be designed to treat either shallow translational slides, deep circular slips or wedge failures. With shallow failures the top 2m of soil can be treated. With deep failure mechanisms, field data and the results of global stability analyses can be used to identify a target depth requiring treatment. The electrode array can then be installed with electrical insulation around the upper parts of the electrodes to target the electrokinetic treatment to the appropriate zone.

Orientation of the electrodes depends on the nature of the potential slip. In the case of shallow slips and failure planes which do not pass beneath the toe of the embankment the ideal orientation of the anodes/nails is slightly sub-horizontal, in which case the anodes are optimally orientated to act as nails, Davies (2007), Figure 7. Placing the cathodes parallel to the anodes can produce optimum electrical field conditions and simplifies installation; there are also benefits with regard to long term drainage when the cathodes have a sub horizontal orientation.

In the case of a deep slip plane passing beneath the toe, orientation of the electrodes is determined by the geometry of the case. The effects of the soil nail array on slope stabilization factors of safety can be analysed using standard slope engineering software.

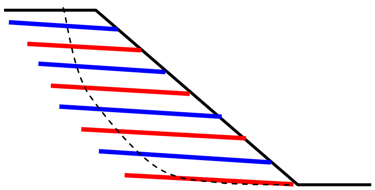

Figure 7 Orientation of electrodes/nails/drains

4.5 *Long-term benefits – drainage*

A critical part of any electrokinetic treatment is removal of water and gas at the cathode. This is achieved with EKG materials by having the cathode formed as a porous polymeric pipe (geodrain). By orientating the cathodes in the embankment at a sub-horizontal angle drainage occurs naturally. Once the electrokinetic treatment is complete the cathodes are retained as permanent drains, Figure 7.

In the case of deep seated failures not all of the cathode drains at the base of the slope can be orientated in a horizontal plane. However, this is usually of secondary importance as drainage of the top of the slope to lower the phreatic surface is the primary objective.

4.6 *Analysis*

Electrokinetic treatment objectives include:

- Increase the shear strength of materials
- Changes in plasticity
- Consolidation of soft materials
- Return to peak shear strength values
- Provide additional drainage
- Provide reinforcement

A series of model tests have been conducted in China to study the effect of EK reinforcement on increasing the stability of saturated soft clay slopes. The EK material used in the tests was formed from electrically conductive plastic with a resistivity of 0.064Ωm, (Zhuang et al 2006).

Analysis of the results of the tests lead to the development of a new analytical theory for electrokinetic strengthening based on energy analysis. The new method has been found to be applicable for both saturated and unsaturated soil during the consolidation process if the soil is saturated at the beginning of the process, (Zhuang, 2005). A numerical simulation program for electro osmosis based on the energy analysis theory has been developed to simulate the model tests.

Practical analysis of electrokinetic strengthening of slopes and tailings dams can be undertaken using the procedure detailed in the Design Manual for Roads and Bridges, UK, (1994) for soil nailing. The analysis requires the following steps:

- Develop model to show failure mechanisms (compare circular v. wedge modes).
- Determine relevant parameters for electrokinetic treatment (w_c, K_e, K_h, M_v, E_c)
- Parametric study to determine influence of increase in c' and Φ'
- Detailed electrokinetic design
- Add the effect of anodes acting as reinforcement (bonus)
- Determine porewater pressures from maximum groundwater profile (controlled by cathode drains)

Details relating to the determination of soil resistivity, electroosmotic paramenters, current demand and electrode layout are provided in Jones *et al* (2008).

4.7 *Permanency of treatment*

A major consideration is the permanency of any electrokinetic treatment to improve the strength of a failing slope. This is considered in Table 4.

Table 4 The permanency of electokinetic strengthening of slopes/soft soil

EKG treatment component	Effect on stability of over consolidated soil	Effect on alluvium/ normally consolidated soil
Reduction in porewater pressure	Increase in undrained shear strength – **Non-permanent** (depending on ability of water to re-infiltrate). If there is long term drainage installed this may extend dissipation of porewater suction.	Consolidation under increased suction (especially under saturated conditions). Increase in peak undrained shear strength **Permanent**

Soil Nailing	Mechanical reinforcement **Permanent**	Mechanical reinforcement **Permanent**
Enhanced soil/nail bond	Improved performance of soil nails - **Permanent**	Improved performance of soil nails - **Permanent**
EKG cathode passive drainage	Avoid build up of pore pressure and extend the period of suction dissipation -**Permanent**	**Permanent**
Electo-chemical pre-cipitation/ hardening	Cementation in the zone around the anode, precipitation in the zone around the cathode. Increase in cohesion and reduction in plasticity. Option for CEC by conditioning with lime - **Permanent**	Cementation in the zone around the anode, precipitation in the zone around the cathode. Increase in cohesion and reduction in plasticity. Option for conditioning with lime - **Permanent**

Table 4 shows that Electrokinetic treatment is permanent except in the case of the strengthening of over consolidated soils. These can be strengthened but chemical precipitation via the anode during the treatment phase and this is permanent.

5 CASE HISTORY; ELECTOKINETIC STABILIZATION OF A RAILWAY EMBANKMENT

There are 20,000 km of earth structures (cuttings and embankments) on the UK highway and rail networks. Few were built to modern geotechnical engineering standards. Due to the development of residual strength with age and the increase in climate change the ongoing maintenance and remediation that these structures has become a major engineering issue for many UK infrastructure owners.

Toe weighting and/or slope regrading is commonly used to tackle the problem, but these do not address the problem of shrink-swell or pore water pressure changes and may delay failure rather than prevent it. In addition, these methods can consume large quantities of primary aggregate and energy and are becoming less viable.

Network Rail (UK) identified electrokinetic ground treatment as a novel slope treatment method which could:

- Stabilise the slope
- Address pore pressure changes
- Address shrink-swell behaviour
- Require only modest access owing to the absence large plant
- Involve low relative energy consumption

On behalf of Network Rail a trial was conducted on a 22m stretch of a 9m high Victorian embankment. The embankment had been constructed by end tipping a mixture of weathered London Clay and other material such as brick and stone fragments onto underlying alluvium and terrace gravels, Figure 8. An assessment of the embankment identified several sections as unstable. Inclinometer readings indicated a slip surface at approximately 2.5m depth, which could either be a shallow translational slide or a deeper circular failure. Stability calculations indicated a FoS for the slope of 1.0.

5.1 *EKG treatment*

The EKG treatment was designed to accommodate either of the identified failure mechanisms. The treatment was based around an array of EKG electrodes installed at 2m centres in the form of tessellating hexagonal cells, with the hexagon being defined by anode stations and a central cathode. The EKG electrodes were installed in 10 days by a two man team, Figure 9. Upon application of a DC potential (60-80V) electroosmosis forced water to flow from the soil adjacent to the anodes to the cathodes. The treatment took six weeks and resulted in:

- Dewatering from the cathodes >25 times that from control drains.
- Cation exchange, causing a reduction in plasticity and shrinkage characteristics.
- An increase in groundwater temperature from $10^{O}C$ to $20^{O}C$.
- DC power consumption was $11.5kWhrs/m^3$ of soil treated.
- Improvements in shear strength parameters (c' and Φ')
- A 263% improvement in the bond strength of the anodes acting as nails, Figure 10.
- Slope movement tending to zero after treatment.

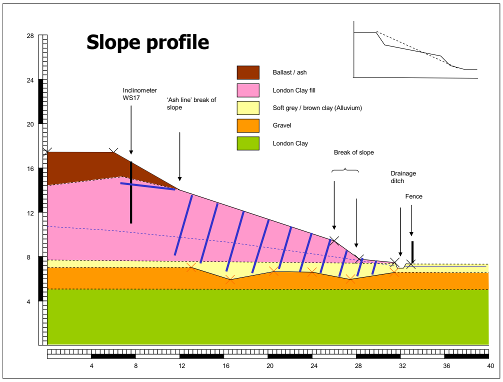

Figure 8 Cross section of the slope showing the stratigraphy, postulated failure planes and location of the EKG electrodes

Following EK treatment the anodes are retained as permanent soil nails and the horizontal cathodes are retained to act as permanent drainage.

Figure 9 Installation of anodes and cathodes

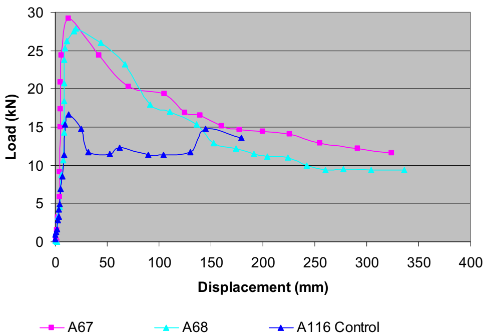

Figure 10 Anode pullout test results

5.2 *Post treatment analysis*

Slope stability analyses were undertaken pre and post treatment. Input data was the lowest measured values for the improvements in shear strength parameters and the lowest measured values for improvements in nail bond strength. The analytical results are shown in Table 5.

Table 5 Results of slope stability analyses

Analysis	Reinforcement	FoS (ULS)
Pre EK treatment	No	0.96
Post EK treatment	No	1.47
Post EK treatment	Yes	1.71

5.3 *Costs*

Previous to the EK treatment, a number of sections of the embankment had been repaired/stabilized using conventional toe weighting by the construction of gabion walls and slackening the slope. A cost analysis comparing like for like slope stabilisation using the EKG method with the use of gabion baskets and slope slackening, indicated that the EKG treatment produced cost savings of 26%.

5.4 *Carbon footprint*

In addition to a reduction in cost EK stabilization of slopes can also deliver a significant reduction in the carbon footprint. Comparison of the EK treatment with the alternative gabion baskets and slackening the slope method which had been used adjacent sections of the embankment showed a reduction in the carbon footprint of over 70%. The calculation was undertaken using the UK Environment Agency's carbon calculator and methodology to determine embodied CO2 of materials and carbon emissions of construction projects, Environment Agency (2007).

5.5 *Induced currents*

Issues have been raised regarding the possibility of 'stray' currents. For clarification, this term is used to denote electric currents which do not flow where intended and are caused by two mechanisms:

- Direct conduction
- Induced currents

An analysis of the EKG treatment indicated that such currents are negligible.

CONCLUSIONS

In this paper the concepts associated with soil consolidation and strengthening of weak soils and failing slopes by means of electrically conductive geosynthetics (EKG) have been described. A Case History shows that the technology can provide technical benefits in addressing all aspects of a failing slope and is competitive in terms of cost when compared with existing methods. In addition, the EK technique provides environmental benefits in that it has a significantly reduced carbon footprint when compared with alternative construction methods.

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