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Soil consolidation and strengthening using electrokinetic geosynthetics – concepts and analysis

Jones, C.J.F.P. & Glendinning, S.
School of Civil Engineering and Geosciences, Newcastle University, UK

Huntley, D.T. & Lamont-Black, J.
Electrokinetic Ltd., UK

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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 embankments and cuttings 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 are in danger of collapse. 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 reinforcement.

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, 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:

- Minimal or effectively zero 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.

2 ELECTROOSMOTIC CONSOLIDATION

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:

$$Q = k_h\ i_h\ A \tag{1}$$

Where k_h is the hydraulic conductivity, i_h is the hydraulic permeability produced by the surcharge loading and A is the area.

Electroosmotic consolidation can be expressed by a similar equation:

$$Q = k_e\ i_e\ A \tag{2}$$

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 can be illustrated by comparing the electroosmotic and hydraulic permeabilities of a range of soils, Figure 1.

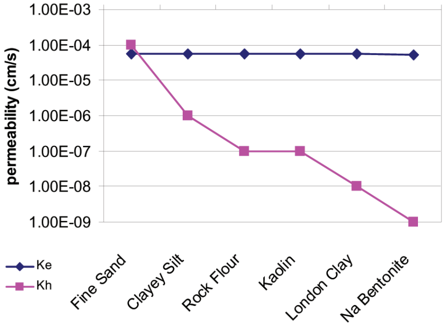

Figure 1. Electroosmotic versus hydraulic permeability.

2.1 *Concept of Electroosmotic Consolidation*

The concept of electroosmotic consolidation of a low impermeable soil mass is illustrated in Figure 2.

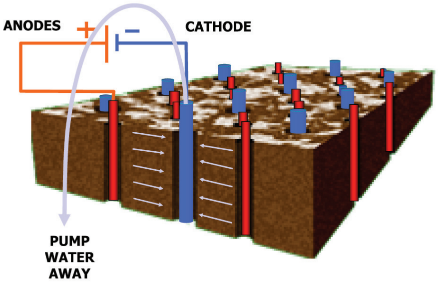

Figure 2. Concept of Electro-osmotic consolidation.

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;

$$u = k_e \gamma_w V / k_h \tag{3}$$

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):

$$\sigma' = \sigma - u \tag{4}$$

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.

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 electro-osmotic 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. 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.

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

2.2 *Combined electroosmotic consolidation and surcharging.*

Electro-osmosis may be combined with conventional surcharging where electro-osmosis 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 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

3.1 *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 1.

3.2 *Electroosmotic permeability*

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

Table 1. 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, 0.3–1.5 MPa
Disk Electrode	✓✓✓	0.05–0.005 S/m
Permeability	✓✓✓	<10-8 m/s
Undrained shear	✓✓	<55 kPa
Drained shear	✓	$\phi' < 30°$
E-O cell	✓✓✓✓	Not applicable
E-O box	✓✓✓✓	Not applicable

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

3.3 *Electrical resistivity*

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

$$\sigma = 1/\rho \tag{5}$$

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 electro-osmosis installation will draw a high current and may not be economic.

3.4 *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.

3.5 *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 3.

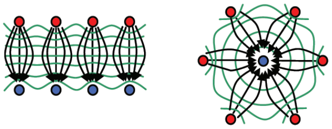

Figure 3. Flow paths for rectangular array (left) and hexagonal array (right).

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:

$$I_t = ncs\sigma V/L \tag{6}$$

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.:

$$\sigma_{\text{fied}} = 0.1\sigma_{e\text{–}o\ \text{cell}} \tag{7}$$

4 STENGTHENING OF SLOPES

Due to changes in weather patterns a growing number of previously stable structures are in danger of collapse. 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 reinforcement.

4.1 *Concept of EKG strengthening*

The concept of EKG strengthening of a slope is shown in Figure 4. 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 *Analysis*

The analysis of electrokinetic strengthening of slopes requires the following steps:

- Identify the potential failure planes

- Identify the relationship between the shear strength of the soil associated with the potential slip planes, Figure 5
- Select of target shear strength of soil to produce stable conditions and hence reduction in water content required, Figure 5
- Determine electroosmotic permeability, (3.2)
- Determine soil resistivity (3.3)
- Select electrode configuration
- Determine electrode layout
- Estimate current demand (3.6)
- (Determine factor of safety of slope assuming the electrodes have a secondary role as reinforcement)

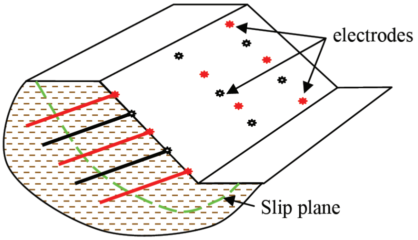

Figure 4. Electrokinetic strengthening of slopes.

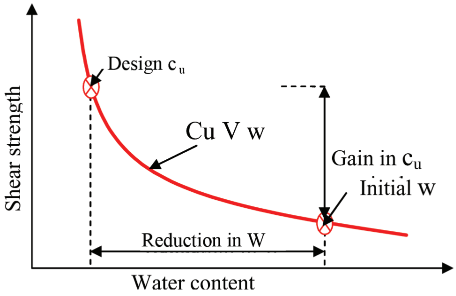

Figure 5. Calculation of reduction in **w** to achieve required increase in $\mathbf{c_u}$ (After Pugh 2002).

4.2.1 *Electrode configuration*

The cathode electrodes need to be in the form of a drain as in para 3.4. Electrodes acting as anodes require a means of gas elimination but do not need to drain water.

5 CONCLUSIONS

In this paper the concepts associated with soil consolidation and strengthening by means of electrically conductive geosynthetics (EKG) have been described.

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