New Horizons in Earth Reinforcement – Otani, Miyata & Mukunoki (eds)

Electrokinetic soil nailing for the strengthening or repair of failures of clay slopes and cuttings

J. Lamont-Black, D. Huntley & C.J.F.P. Jones
Electrokinetic Ltd., United Kingdom

S. Glendinning & J. Hall
Newcastle University, United Kingdom

ABSTRACT: Traditional methods for the repair of cuttings have included slackening the slope by the provision of dwarf walls at the toe or the acquisition of additional land, although the latter is seldom possible. Other methods of repair can include soil nailing and/or the provision of reinforced soil berms to increase stability. As the failures are predominantly caused by the development of residual shear strength conditions or uncontrolled pore water pressures, an obvious remedial method would be to effect a reduction in pore pressures and an increase in the shear strength of the soil. This can be achieved by electroosmosis as part of an electrokinetic treatment. Electroosmosis can be used, either to aid construction of remedial works or as a means to effect permanent improvement. A major advantage of the process is that it can be installed without excavation of the cutting and with the use of limited equipment. Treatment is rapid and the strengthening can be permanent.

1 INTRODUCTION

There are a growing number of shallow slip failures in existing railway cuttings and embankments involving fine-grained soils and an expectation that this problem will increase with climate change. Failures in cuttings pose particular problems, not the least of which are the need to maintain rail traffic and the difficulty of access for large/heavy plant. Traditional methods for the repair of cuttings have included slackening the slope by the provision of dwarf walls at the toe or the acquisition of additional land, although the latter is seldom possible. Other methods of repair can include soil nailing and/or the provision of reinforced soil berms to increase stability. The paper considers the use of electrokinetic geosynthetic (EKG) drains and electrokinetic soil nails to strengthen failing cuttings and slopes and provides details of the design and analytical procedures that can be adopted together with details of a case history.

1.1 *Use of electrokinetics in slope stabilisation*

Cassagrande (1983), explained the benefits of using electroosmosis in civil engineeing when he wrote: "Electroosmosis when applied to fine grained soils is an effective method for increasing strength. This increase is principally the result of tension produced in the pore water as the water content is reduced and menisci are formed, and is also partially due to bonding and cementation of the soil particles.

Electroosmosis is also effective for control of seepage forces, which is highly beneficial for stabilizing slopes in fine grained cohesionless soils.

For cohesive soils, electroosmosis usually results in an increase in the plasticity index, especially near the anode. In combination with a reduction in the water content, the change in plasticity more quickly reduces the liquidity index, and thus more effectively increases the strength of the soil…. The coefficient of electroosmostic permeability (k_e) may be 2 or 3 orders of magnitude greater than the hydraulic coefficient of permeability (k_h), which explains the relatively rapid benefits of electroosmosis".

The difference in the coefficients of electroosmotic and hydraulic permeabilities referred to by Casagrande and which lends such and advantage to electroosmosis when applied in fine grained soils is illustrated in Figure 1. Despite the apparent benefits of electroosmosis and the success of some historical applications, the limitations of conventional electrodes have meant that the technique has received relatively little attention in geotechnical engineering. These limitations related to problems associated with the electrodes including, corrosion, build-up of surface electrical resistance, excessive power consumption, poor drainage of water, undesired entrapment of gas, and the inability to effect polarity reversal.

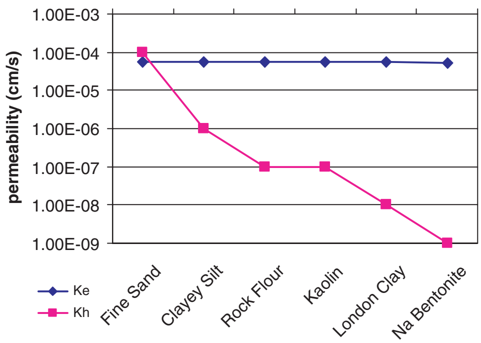

Figure 1. The coefficients of electroosmotic permeability k_e and hydraulic permeability k_h for a range of soils. Note that whilst k_h decreases exponentially with decreasing grain size k_e remains effectively constant across all grain sizes.

EKG technology has been developed to overcome the practical problems associated with the application of electroosmosis (Jones*et al.*, 2005).

2 EKG TO STABILISE CLAY SLOPES

The primary objective in the maintenance of slopes is to identify potential failing slopes and to return them to full stability before failure occurs. In the case of railway cuttings this can be difficult, as although the identification of potential failures is possible, treatment is difficult. The use of heavy equipment at the top of the slope is not desirable as it could initiate failure and treatment of the cutting from track level results in disruption of trains and the incurrence of fines.

As the failures are predominantly caused by the development of residual shear strength conditions or uncontrolled pore water pressures, an obvious remedial method would be to effect a reduction in pore pressures and an increase in the shear strength of the soil. This can be achieved by electroosmosis. Electroosmosis can be used, either to aid construction of remedial works or as a means to effect permanent improvement. A major advantage of the electroosmosis process is that it can be installed without excavation of the cutting and with the use of limited equipment. Treatment is rapid and the strengthening can be permanent.

In using EKG to stabilise clay slopes, EKG treament offers immediate effects and long-term benefits. The concept of EKG strengthening of a slope is shown in Figure 2. The orientation of the electrodes is selected to intercept any potential failure plane. Electoosmotic dewatering of the slope results in a reduction in pore water pressure and an increase in the shear strength of the soil, reducing the risk of a slip plane developing.

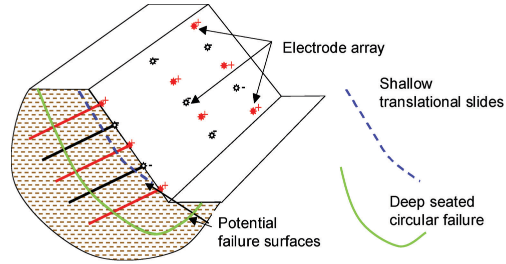

Figure 2. Electrokinetic strengthening of slopes.

2.1 *Immediate effects*

The immediate effect of the application of an electrokinetic force is a reduction of pore water pressure and a reduction of water content. Reductions in pore water pressure and electroosmotic flow are given by, (Mitchell 1993);

$$u = - k_e/k_h.\ g_w.\ V \qquad (1)$$

$$Q = k_e.V/L.\ A \qquad (2)$$

where: u = porewater pressure, k_e = coefficient of electroosmotic permeability, k_h = coefficient of hydraulic permeability, g_w = density of water, Q = electroosmotic water flow, V = voltage applied between electrodes, L = spacing between electrodes (anode – cathode), A = area.

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 permeabilities. Therefore, electroosmosis is most effective in fine-grained soils such as clays and silts. 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, Figure 3.

2.2 *Long-term benefits*

By choosing the appropriate combination of anode and cathodes and a specific electrode array or style of installation, the treatment will provide the following long-term benefits, Figure 3.

2.2.1 *Reinforcement*

The anodes remain in-situ as stiff soil nails. The effects of the soil nail array on slope stabilization factors of safety can be analyzed using standard slope engineering software.

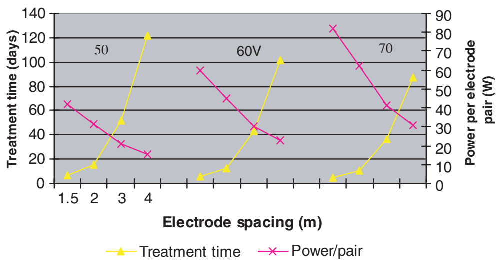

Figure 3. Relationship of electrode spacing applied voltage and treatment time for a slope stabilization project.

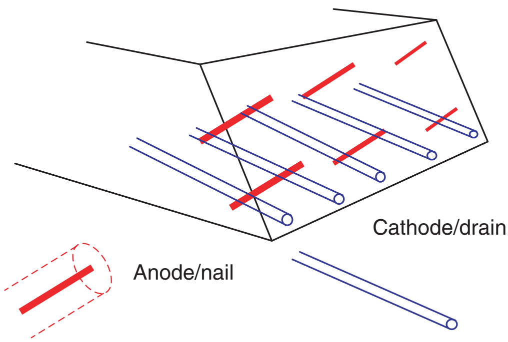

Figure 4. Arrangements of EKG electrodes to stabilize slope and then act as long term soil nails and drains.

2.2.2 *Cementation*

The anodes can be formed to have a partially sacrificial function which will produce several distinct effects:

- ions precipitated from solution cement the clay around the anode thus stiffening the clay and forming a 'mini pile'; effects such as these have been noted (Milligan, 1994).
- create a very strong bond with the anode/nail.
- the formation of a larger effective surface area for the nail thus increasing its pullout capacity.

2.2.3 *Drainage*

Cathodes can be inserted into the ground and oriented so as to act as permanent drains after active electrokinetic treatment has ceased, Figure 4. This sets up an irregularly shaped electric field and attention has to be given when designing the array to focus the strongest parts of the electric field on the weakest zones of soil in the slope.

2.2.4 *Analysis*

The following analytical procedure can be assumed base on (HA 68/94: 1994).

1. Determine slope geometry and soil properties including the ground water flow conditions.
2. Identify potential failure planes.
3. Identify the relationship between shear strength and water content of the soil in the cutting.
4. Select target shear strength to produce a stable cutting.
5. Compute the reduction in water content to provide shear strength in (4).
6. Select electrical layout.
7. Determine treatment time and current design.
8. Following electro kinetic treatment reanalyse with the anode electrodes operating as soil nails (base bond strength nail/soil on an estimation of the residual negative pore water pressure).

2.2.5 *Depth of treatment*

Slope stabilization with EKG can be designed to treat either shallow translational slides or deep circular failures. With shallow failures the top 2 m of soil can be treated. With deep circular slips, field data and the results of global stability analysis 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 ensure their targeted action.

3 CASE STUDY

A number of cuttings on Brunel's London – Bristol main railway line constructed circa 1850 are cut at approximately 35° into clay materials. Recently these slopes have shown repeated movement, especially after heavy rain. Factors involved in the instability are thought to be a combination of: high pore pressure in the clay; high water content in the clay; and the ineffectiveness of counterfort drains (which were installed as a measure to improve slope drainage). A number of slope remediation techniques have been implemented on the site, including weighting of the toe of the slope, and excavation and trimming the slope to a shallower angle. These methods have been generally successful but they have limitations in that they involve:

- Significant time to mobilise and complete.
- Do not deal with the core problem i.e. the high weakness of the clay itself and its high pore water pressures.
- Require heavy plant and machinery, which may pose safety hazards when situated at the top of a moving slope.
- Taking possession of the track thus incurring cost penalties.

3.1 *EKG treatment*

Stabilization of the cutting in the area of the counterfort drains is being undertaken using a single treatment which combines electroosmotic stiffening of the soil, electroosmotically enhanced soil nails and permanent

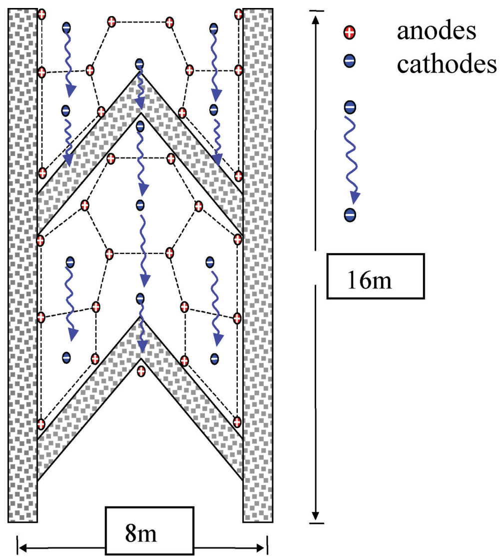

Figure 5. EKG treatment array, based on a hexagonal array which has been adapted to fit within the layout of a slope panel.

Figure 6. EKG cathode and drain.

drainage. The objectives of the remedial treatment are both short and long term. The short term objectives are to achieve stability and reduce the pore water pressures. The long term objectives are to increase stability of the cutting, improve drainage and improve the strength of the Lias clay forming the cutting.

Calculations using assumptions of the site characteristics show that treatment using an electrode spacing of 2 m and an applied potential of 60 V would produce a theoretical negative pore water pressure of – 300 kPa and a 2% reduction in water content in 6–10 days. Figure 5 shows the layout of the anode and cathode electrodes relative to the existing counter-fort drains into which the cathodes discharge. Figure 6 shows the form of an EKG electrode/drain.

REFERENCES

Casagrande, L. (1983) "Stabilisation of soils by means of electro-osmosis, state-of-the-art." *Journal of the Boston Society of Civil Engineers Section,* **69**(2), 255–302, ASCE.

Design Manual for Roads and Bridges (1994) "Design Methods for the reinforcement of highway slopes by reinforcing soil and soil nailing techniques", HA 68/94, *Geotechnics and Drainage, Part 4*.

Glendinning, S., Jones, C. J. F. P. & Pugh, R.C., (2005) Reinforced soil using cohesive fill and electrokinetic geosynthetics (EKG), *International Journal of Geomechanics,* **5** (2), 138–146.

Milligan, V. (1994) "First application Of Electro-Osmosis To improve Friction Pile Capacity-Three Decades Later", *13th Int. Conf. on Soil Mech. and Found. Eng.,* **5**, 1–5, New Delhi, India, Pub. Balkema.

Mitchell, J.K. (1993). *Fundamentals of Soil Behaviour*. 2nd Edn., Pub. John Wiley & Sons Inc, New York, USA.