Engineering Sustainability
Volume 167 Issue ES3
The environmental sustainability of electrokinetic geosynthetic strengthened slopes
Jones, Lamont-Black, Glendinning, White and Alder
ice | proceedings

Proceedings of the Institution of Civil Engineers
Engineering Sustainability 167 June 2014 Issue ES3
Pages 95–107 http://dx.doi.org/10.1680/ensu.13.00015
Paper 1300015
Received 18/04/2013 Accepted 14/01/2014
Keywords: embankments/geotechnical engineering/rehabilitation, reclamation & renovation

ice
Institution of Civil Engineers
publishing

The environmental sustainability of electrokinetic geosynthetic strengthened slopes

Colin J. F. P. Jones MSc, PhD, CEng, FICE
Director, Electrokinetic Limited, Newcastle upon Tyne, UK

John Lamont-Black PhD
Managing Director, Electrokinetic Limited, Newcastle upon Tyne, UK

Stephanie Glendinning PhD
Professor, Department of Civil Engineering and Geoscience, Newcastle University, Newcastle upon Tyne, UK

Chris White MSc
Engineer, Electrokinetic Limited, Newcastle upon Tyne, UK

David Alder MEng
Postgraduate Student, Department of Civil Engineering and Geoscience, Newcastle University, Newcastle upon Tyne, UK

Failures of cut and embankment slopes are common and expected to increase. Conventional repair techniques include acquiring additional land, reducing the slope angle, installing drainage improvements, soil nailing and/or providing structural support. All of these methods have technical limitations and most cause considerable environmental disturbance. However, new stabilisation options that are more effective and economical than traditional approaches are becoming available, one of which is electrokinetic geosynthetic treatment of failing or failed slopes. The benefits of electrokinetic geosynthetic treatment in terms of engineering sustainability include reduced cost, reduced 'carbon dioxide footprint', fewer heavy goods vehicle movements, zero waste removal, minimal material import, reduced noise and vibrations, improved air quality, preservation of the seed bank and soil environment, minimal vegetation clearance with almost all trees being retained, no visual impacts, no disruption to passing motorists and less damage to root protection areas. Protection of the habitat is also beneficial to nesting birds, amphibians, dormice and reptiles. The paper provides a brief description of the electrokinetic geosynthetic treatment method and illustrates the engineering sustainability with two case histories.

1. Introduction

There are 20 000 km of earth structures (cuttings and embankments) on the UK highway and rail networks. Many are old, and were not built to modern geotechnical engineering standards. The gradual deterioration in condition over time means that many slopes currently suffer serious instability and/or serviceability problems. The ongoing maintenance and remediation that these structures now require to extend their life has become a major engineering issue for many UK infrastructure owners.

Failures of cut and embankment slopes are caused by a variety of factors, including the development of residual conditions (age), changes in pore-water pressures, slope geometry, hydrology and groundwater, and seasonal climate variations. In the future, changes in rainfall patterns as a result of climate change have the potential to increase slope instability in certain regions (Hughes *et al.*, 2009; Kilsby *et al.*, 2009).

The choice of slope repair and stabilisation method has traditionally depended on site conditions, logistics and cost. Conventional stabilisation options include acquiring additional land, reducing the slope angle, installing drainage improvements, soil nailing and/or the provision of structural support. All of these methods have technical limitations and some do not address the problem of shrink–swell or pore-water pressure changes, and can only delay failure rather than prevent it. Some are very costly and most have severe implications to the preservation of the flora and fauna that may exist on the site in question. As sustainability becomes increasingly important to asset owners, a number of these methods, which can consume large quantities of primary aggregate and energy, are becoming less viable. An additional factor is that some of the techniques involve the use of large plant such as piling equipment, which requires lane closures; this in turn can lead to additional economic and social costs due to delays incurred by the travelling public and disruption to commerce.

The above considerations indicate that there is a requirement for alternative methods of slope stabilisation of embankments and cuttings that will meet the three core sustainability elements identified as economic, environmental and social. Thus the alternatives should

- stabilise the slope
- address pore-water pressure changes
- address shrink–swell behaviour

- require only modest access
- minimise the import/export of materials and aggregates
- not involve the use of large plant
- have low relative energy consumption
- have minimal negative environmental and social impact.

One alternative remediation technology is electrokinetic geosynthetic (EKG) treatment. This method can meet the above criteria and achieve slope stabilisation and strengthening with significant reductions in cost and 'carbon dioxide footprint' and reduced environmental and social impacts. This paper gives a brief description of the EKG slope stabilisation technique, highlighting how it differs from other methods and illustrating the improved engineering, environmental and social benefits – including reductions in cost – that the method provides. These benefits are illustrated using recent case histories.

2. Electrokinetic geosynthetics

Conventional geosynthetics play a passive role in ground engineering. For example, geosynthetic reinforcement provides tensile resistance only after an initial strain has occurred and geosynthetic drains provide a passage for water but do not cause water to flow to the drain. The scope of geosynthetics applications can be extended 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 standard geosynthetic functions. This can be achieved by combining electrokinetic phenomena with the traditional geosynthetics functions of drainage, filtration, containment and reinforcement to form an EKG. Thus, an EKG is both a geosynthetic and also an electrode (anode or cathode) and can take any form (e.g. reinforcement grid, geotextile sheet, drainage tube or containment bag).

EKG technology works by harnessing electro-osmosis, which is the water flow that occurs in response to an imposed voltage gradient (typically 60–80 V). In fine-grained soils, electro-osmosis can achieve flow rates up to four orders of magnitude greater than hydraulic flow; as a result, electrokinetic dewatering is a rapid method of improving weak soils or fills. EKG treatment is inherently and beneficially self-selecting with respect to the materials that need strengthening because soft, weak materials respond with greater change than stiffer materials. In addition, EKGs can be used to control the physical, chemical and electrical boundary conditions. Figure 1 shows the principal processes that are active in a section of clay-rich soil under electrokinetic treatment. Details of the development of EKG technology and its applications have been described by Jones *et al.* (2008).

3. Electrokinetic strengthening and repair of slopes

Electrokinetic strengthening of soil has been undertaken by a number of practitioners, most notably Casagrande (1952, 1983). Historically, the technique has been under-utilised for a number of reasons, including ineffective control of boundary conditions and ineffective electrodes, which either cannot cope with different materials or are not able to control fluxes. EKGs were developed to realise the potential of electro-osmosis by addressing these limitations.

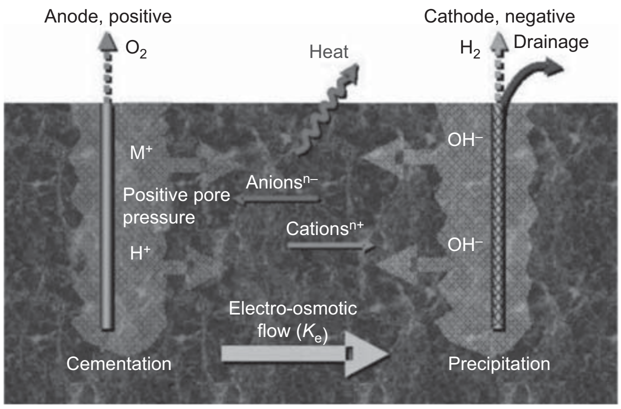

Figure 1. Electro-osmotic flow in clay soil

EKG treatment of slopes is initiated by the installation of an array of EKG anode and cathode electrodes using lightweight self-climbing rigs (Figures 2 and 3). The EKG anodes are formed as porous tubular elements, through which conditioning fluids can be introduced, which are driven into the ground with a percussive hammer. The cathodes are formed as geosynthetic tubular drains with a filtration element to prevent blockage and contained within a conductive mesh. The cathodes are located within pre-drilled holes. After electrokinetic treatment, the EKG anodes are converted to soil nails by the addition of reinforcement grouted within the tube. The EKG cathodes are retained as permanent drains. The

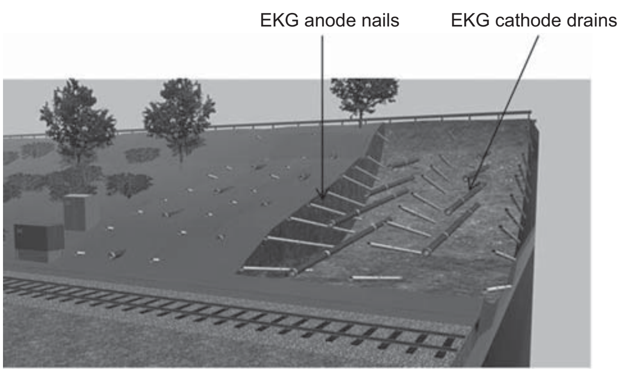

Figure 2. Array of EKG anodes and cathodes

Figure 3. Small self-climbing rig for installation of EKG electrodes

orientation of the electrodes is chosen to optimise both reinforcement and drainage functions. Once installed, the anodes and cathodes are connected to a portable computer-controlled DC power supply. As shown in Figure 4, EKG treatment comprises four components

- dewatering by electro-osmosis
- reinforcement
- drainage
- soil modification.

In the case of slopes, the electrokinetic treatment is typically of 6–7 weeks' duration. Details of the design and analysis of electrokinetic remediation of slopes have been provided by Lamont-Black and Weltman (2010), Jones (2011) and Lamont-Black *et al.* (2012).

3.1 Electro-osmosis

An applied voltage gradient creates electro-osmotic flow from the anode to the cathode. By draining the cathode and preventing water ingress at the anode, there is a major drop in pore-water pressure (of the order of −280 kPa), which causes an immediate increase in effective stress. In soils, there is a strong correlation between undrained shear strength and water content, whereby a small reduction in water content can result in a significant increase in shear strength. In addition, ion migration from the anode results in cementation. Around the cathode, precipitation of hydroxide salts occurs due to the presence of hydroxide (OH^{-1}) ions in the soil (Figure 1). The

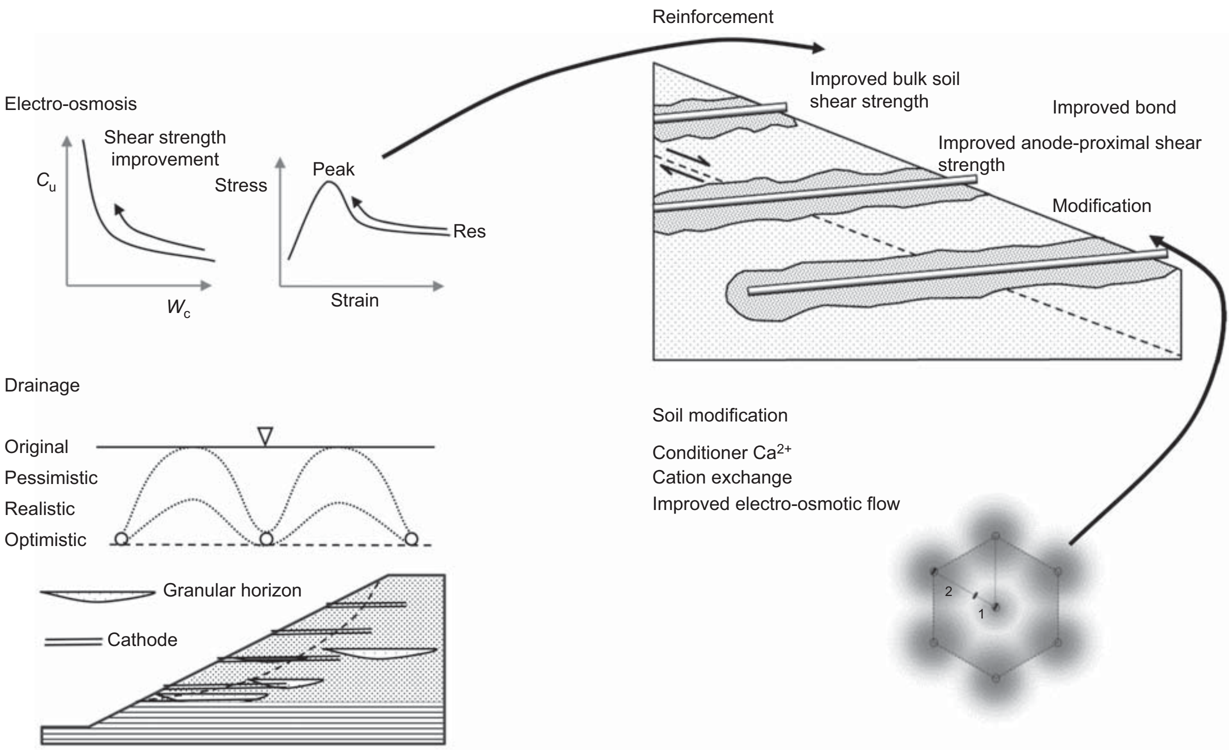

Figure 4. Components of EKG slope stabilisation (C_u, undrained strength; W_c, water content)

cementation and precipitation cause a reduction in soil plasticity and an increase in its cohesion.

3.2 Reinforcement

During electrokinetic treatment, the soil around the EKG anode becomes cemented due to electrochemical changes initiated by ion migration from the anode; these can be enhanced or controlled by selecting the structure and composition of the anode, together with optional use of conditioning fluids. Cementing round the anode increases the anode–soil bond and the enhanced bond has been shown to be permanent (Milligan, 1994). Furthermore, the enhanced bond is not confined to clay materials – a sixfold increase in soil–nail bond has been found in electrokinetically treated silty sand, showing that the method is effective for use in heterogeneous ground conditions (Pugh, 2002).

Some codes of practice associated with the design of soil nailing express concern about the use of reinforcement for permanent works in cohesive soils. Geoguide 7 (GEO, 2008) identifies fill slopes formed by end tipping without compaction as loose fill. In these cases, soil nailing is an option for upgrading provided that the degree of compaction of the fill slope is not less than 75% and there is no sign of distress, history of movement, seepage or weak zones. The US Federal Highway Administration (FHWA, 1989) warns that nail capacity may not be economically developed in highly plastic cohesive soils subject to creep, even at relatively low load levels. Soil nailing should not be considered in the following soil profiles.

- Below permanent groundwater tables unless a complete drainage system is installed.
- Ground with water pressure present at the face.
- Cohesive soils with a liquid limit greater than 50 and with a plasticity index greater than 20.
- Soils with a consistency index (I_c) of less than 0·9; the consistency index is defined as $I_c = (W_l - W)/(W_l - W_p)$ where W_l is the liquid limit, W is the natural water content and W_p is the plastic limit.

These concerns relate to potential problems of soft, low-strength soils, a high moisture content and pore-water pressure, creep, and low bond strength between the reinforcement and the soil. EKG treatment directly addresses these concerns in the following ways.

- Long-term drainage discourages pore-water pressure build-up and influences the effective stress component of the bond.
- Strengthening and cementation are imparted to the soil into which the nail is inserted.
- The cemented/non-frictional component is independent of pore-water pressure.

The use of hybrid treatment systems involving electrokinetic strengthening of soil is accepted in the revised BS 8006: Part 2 (BSI, 2011).

3.3 Drainage

During electrokinetic treatment, water flows towards the cathodes, resulting in drainage of the slope. Following treatment, the cathodes are left in place to provide long-term drainage. The cathodes are installed with a small sub-horizontal inclination to permit free drainage (Figure 2).

3.4 Soil modification

Electrokinetic treatment of soil has beneficial effects in changing the chemical nature of the soil, including cementation, precipitation, cation exchange and (in some soils) changes in particle size distribution. The latter has been reported in electro-osmotic treatments in Canada, UK and USA. In the UK case (London Clay), the cause is believed to be due to flocculation. The physiochemical effects often act together and can be difficult to distinguish. They also act together with consolidation (where it occurs) to increase soil shear strength parameters (c' and Φ'), soil stiffness and reduce soil plasticity (Pugh, 2002).

4. Engineering sustainability relating to slope maintenance and repair

Although embankment/cutting stabilisation schemes are often small in size, they are numerous and failure can be a major disruption to transport and commerce. In addition, due to their undisturbed nature, highway embankments can be rich in wildlife, which in some cases is afforded protection, particularly when the highway lies within an area of special scientific interest. Some highway areas lie within sites of international importance such as special areas of conservation. For these reasons, embankment stabilisation schemes can have significant and long-lasting impacts on wildlife. The clearance of vegetation to enable access for plant and the incorporation of stabilisation materials (e.g. soil nails, lime, retaining walls, soil replacement) is often widespread and some techniques used render replanting impossible, leaving a legacy of stark, bare embankments/cuttings, unfavourable wildlife habitats and unpleasant views for local residents. As reported by Glendinning *et al.* (2009a, 2009b), the retention of vegetation has not only environmental but also structural benefits.

The needs of the environment are recognised in the corporate and business plans of the UK Highways Agency. The 'Customers First' corporate plan emphasises the need to minimise the impact of activities on the environment and those living close to roads (Highways Agency, 2005) while the

2010–2011 business plan describes the successful deliverance of the environment theme as improving the quality of life for both transport users and non-users (Highways Agency, 2010) and the biodiversity action plan (Highways Agency, 2002) relates to the need for support of both habitats and species and emphasises the commitment to minimise the impact of highway works on the natural environment.

The EKG stabilisation technique is fully compatible with the Highways Agency's objectives. Compared with traditional methods, EKG slope stabilisation results in

- fewer heavy goods vehicle (HGV) movements
- zero waste removal
- minimal materials imports
- reduced noise and vibrations
- improved air quality
- preservation of the seed bank and soil environment
- minimal vegetation clearance, with almost all trees being retained
- no visual impacts
- no disruption to passing motorists
- less damage to root protection areas.

The benefits of EKG slope stabilisation in terms of engineering sustainability are now illustrated using two case histories.

5. Case history 1: stabilisation of South Greenford railway embankment

South Greenford railway embankment was constructed during the Victorian age. The embankment has a history of slope maintenance and repair. In 2008, an assessment of slope movements identified several sections as unstable, with some showing movement of more than 6 mm/month. Speed restrictions of 30 mph (≈48 km/h) and 20 mph (≈32 km/h) were imposed on passenger and goods trains, respectively.

The remediation method used in previous repairs was toe weighting using gabions and slope slackening. In 2009, remediation of a failing section of the embankment was undertaken using the EKG technique. Details of the design of the remediation are provided elsewhere (Lamont-Black and Weltman, 2010; Lamont-Black *et al.*, 2012).

The embankment, which was 9 m high with side slopes of 22°, had been constructed by end tipping fill and was formed of a mixture of weathered London Clay and other material such as brick and stone fragments, overlying alluvium and terrace gravels. Inclinometer readings adjacent to the site indicated a distinct slip surface at approximately 2·5 m depth, which could be either a shallow translational slide or a deeper circular failure (Figure 5). Stability calculations undertaken by consulting engineers Tony Gee and Partners indicated a factor of safety 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 2 m centres in the form of tessellating hexagonal cells, with the hexagon being defined by anode stations and a central cathode. The EKG active treatment phase took 6 weeks. A detailed programme of monitoring, together with a comprehensive decommissioning study, was implemented to record

- volume and rate of water removed
- pore-water pressures
- groundwater temperature and quality
- power consumption
- ground conditions, including soil strength testing before and after treatment
- inclinometer deflections
- increase in soil–reinforcement bond (provided by the anodes post-treatment)
- treatment logistics.

5.2 Results: groundwater

Application of the active treatment forced water out of the ground, raising it more than 4 m above the initial groundwater level. Discharge from the active cathodes was more than 25 times that of control cathodes. Groundwater quality monitoring indicated that cation exchange processes were active as part of the treatment, which correlated with a reduction in plasticity and shrinkage characteristics. The treatment caused a gradual increase in groundwater temperature from 10℃ to 20℃.

5.3 Results: electrical energy

The initial array current of 460 A decayed to 180–200 A over a period of 5 d. The overall DC power consumption was 11·5 kWh/m^3 of soil treated. Concern has been raised regarding the possibility of 'stray' currents resulting from EKG treatment. Stray current is a term used to denote electric currents that do not flow where intended and are caused by direct conduction or induced currents. An analysis of the EKG treatment at South Greenford showed that such currents were negligible.

5.4 Results: geotechnical

Before treatment, the embankment comprised a core of relatively strong and firm material underlain by softened embankment fill and alluvium. The near-surface material of the embankment fill was in a softened state. Boreholes drilled during the decommissioning stage demonstrated that the softened material beneath the embankment had improved to become firm. Testing of soils recovered after treatment demonstrated

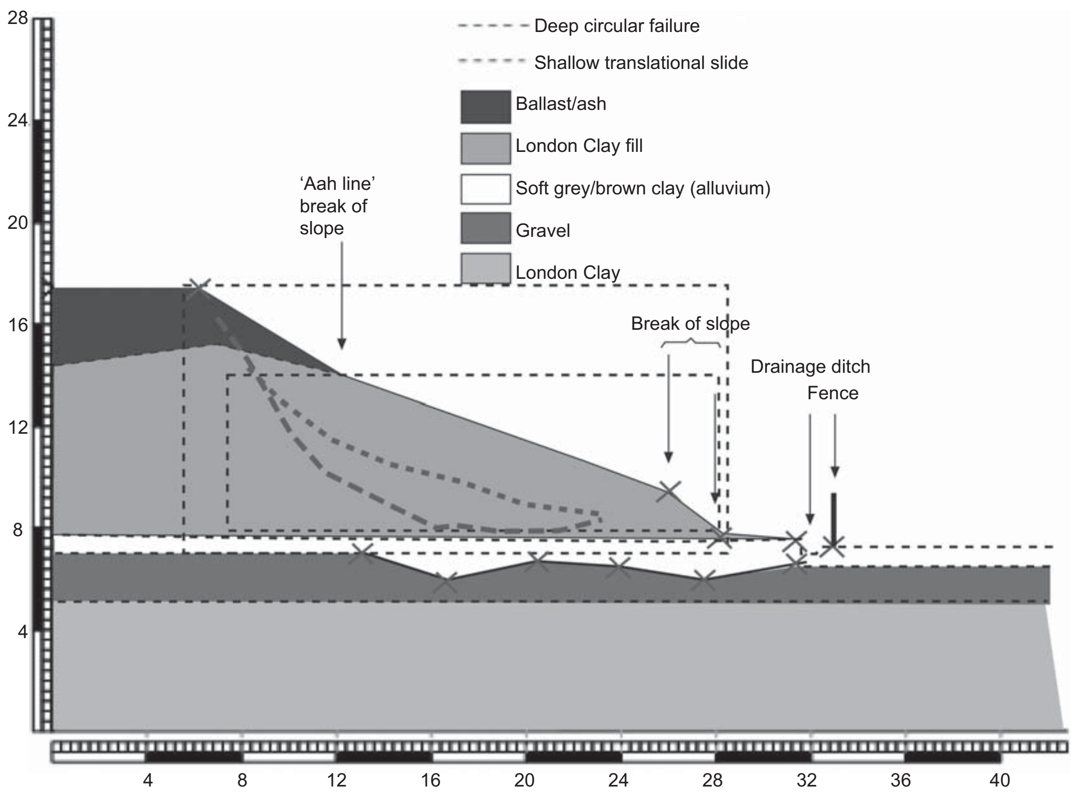

Figure 5. Slope stabilisation at South Greenford (dimensions in m)

improvements in shear strength parameters (c' and Φ') and a reduction in plasticity. Pull-out tests on the anodes demonstrated an improvement in the bond strength of the anodes acting as nails by an average factor of 263% (Figure 6).

5.5 Treatment logistics

Monitored installation rates indicated that the electrodes could be installed in 10 working days by a two-man drilling team with a slope climbing rig (Figure 3). The electrical connection and panel commissioning also took 10 working days (two-man team). By preparing cables during the period of electrode installation, the array could be installed and ready in a period of 10–15 working days. Apart from security and R&D data collection visits, there were no requirements for labour during active treatment.

5.6 Economic benefit

The EKG slope repair was located immediately adjacent to a previous repair based on the use of gabions and slackening the slope, undertaken by the same contractor. The proximity of the two projects allowed direct comparison of the two techniques. Comparison of billed rates showed that the EKG technique reduced the cost of the repair by 26%.

The lower cost of the EKG treatment can be attributed to

- no importation of materials other than the EKG electrodes/drains/nails
- reduced labour force (Table 1)

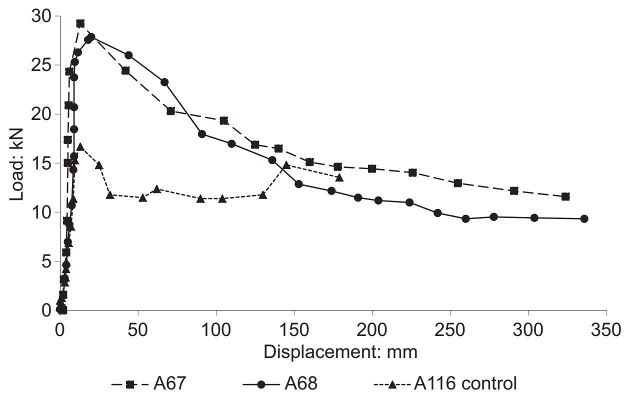

Figure 6. Pull-out tests on EKG nails post-treatment at South Greenford

- the use of small self-climbing plant capable of traversing the embankment and thereby reducing access requirements
- reduced travel and welfare requirements.

5.7 Carbon dioxide footprint

The carbon dioxide footprints of the EKG treatment and the adjacent repair using slope slackening were compared using the Environment Agency's carbon dioxide calculator v3.11 (www.environment-agency.gov.uk). The geometry of the gabion and slope slackening method is shown in Figure 7. At South Greenford, the gabion baskets were 2 m high, which produced a slackened slope angle of 18·7°. The volumes of materials required for the slackened slope solution are shown in Table 2 and the carbon dioxide footprint of the repair is shown in Table 3. The carbon dioxide footprint details for the EKG treatment are shown in Table 4. Comparison of Tables 3 and 4 shows a reduction in the carbon dioxide footprint of 46% for the EKG option.

5.8 Social benefit

The social benefit of using the EKG treatment at South Greenford was small as the site was located adjacent to a golf course. However, the EKG treatment required no offsite storage of materials and a shorter period for the works to be completed. Installation of the electrodes was accomplished without the need for the installation plant to leave the confines of the railway slope.

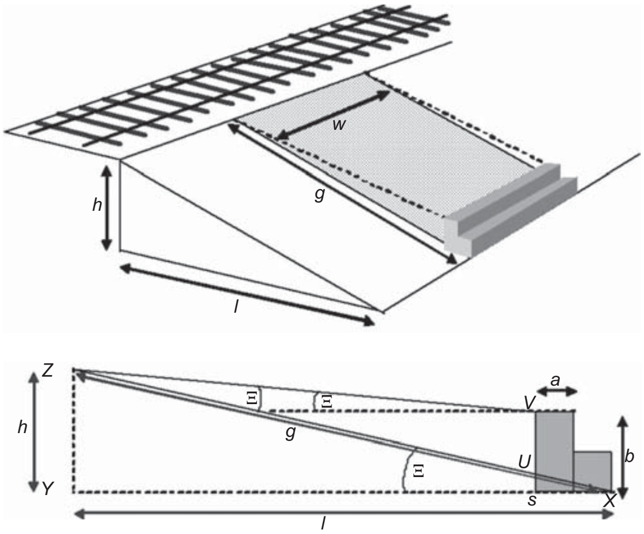

Figure 7. Geometry of the gabion and slope slackening repair at South Greenford

6. Case history 2: stabilisation of A21 Stocks Green highway embankment

The A21 trunk road is a dual-carriageway road south of London, which has developed a number of embankment failures. The embankment was constructed of Weald Clay and the failing section was 170 m long and 7 m high. A previous repair in the summer of 2010 at an immediately adjacent site had been undertaken using soil nailing, and thus the EKG technique could be compared directly with the conventional method. The design life of the EKG solution was the same as the adjacent soil nailing case (60 years). The economic and

	Week										
	1	2	3	4	5	6	7	8	9	10	Total
EKG treatment											
Contractor on site	1	1	1	1						1	5
Security	1	1	1	1	1	1	1	1	1	1	10
Clearance and installation	2	2	2	2							8
Running											
Decommissioning										2	2
Total site staff/week	4	4	4	4	1	1	1	1	1	4	25
Gabion/slope slackening											
Contractor on site	1	1	1	1	1	1	1	1	1	1	10
Security	1	1	1	1	1	1	1	1	1	1	10
Access and site clearance	2	4	4								10
Construct gabions				4	4	4	4				16
Earthworks and compaction							2	2	2	2	8
Total site staff/week	4	6	6	6	6	6	8	4	4	4	54

Table 1. Comparison of labour requirements for EKG treatment and gabion/slope slackening at South Greenford

Slope dimensions	
Width of slope, *w*: m	22·0
a: m	1·0
b: m	2·0
ZX (*g*): m	27·0
Initial slope angle: degrees	22·0
Reduced slope angle: degrees	18·66
ZY (*h*): m	10·1
YX (*l*): m	25·0
Fill characteristics	
Density of imported soil: Mg/m^3	2·0
Density of gabion fill: Mg/m^3	2·0
Material quantities	
Volume of imported fill: m^3	486·4
Mass of imported fill: Mg	972·7
Volume of gabion fill: m^3	44·0
Mass of gabion fill: Mg	88·0

Table 2. Slope dimensions (see Figure 7) and volumes of material for gabion baskets and fill at South Greenford

environmental benefits derived using the EKG stabilisation technique are now summarised.

6.1 Economic benefits

Similar to the South Greenford EKG treatment, the Stocks Green repair required a two-man workforce to install the EKG electrodes using a self-climbing rig working around the trees on the embankment (Figure 8). The EKG repair was undertaken during the winter of 2011 without the need for traffic management or lane closure on the A21. Alternative repair methods would have required lane closure, with significant cost (traffic delay and traffic management costs) and social implications (delays and noise).

The EKG electrodes were installed up the failing slope in alternating columns of anodes and cathodes 1·5 m apart. In total, 10 080 m^3 of soil was treated at an average voltage of 86 V and an average current draw of 713 A. Treatment took 42 d, with an energy consumption of 22·1 MJ/m^3.

The cost of the EKG repair was £4300/m run of the embankment. The cost of the adjacent soil nailing repair was £6100/m run.

6.2 Waste and materials

The EKG technique generates significantly less waste than conventional methods. The only waste generated on the Stocks Green project was a small amount of vegetation that had to be cleared to allow access to the site. Most of this was reused on site as wildlife refugia. Waste removed from the site consisted of leaf litter and small branches that could not be stacked. In comparison, the adjacent soil nail stabilisation method required the felling and removal of all trees and vegetation, together with trimming of the slope and subsequent removal of approximately 35 m^3 of soil per metre of embankment treated (totalling 4500 m^3 soil for the Stocks Green repair).

6.3 Carbon dioxide footprint

A comparison of the carbon dioxide footprints of the EKG treatment and the adjacent soil nailing repair was undertaken, again using the Environment Agency's carbon dioxide calculator (Tables 5 and 6). The EKG repair showed a 48% reduction in carbon dioxide footprint.

Item	Component	Unit of component	Quantity	Carbon dioxide: t/unit of component	Total carbon dioxide: t
Gabion baskets	Steel wire	Mg	1·65	2·830	4·67
Gabion fill	Aggregate	Mg	88	0·056	4·93
Soil fill	Mixed soils	Mg	973	0·023	22·40
Fuel [a]	Diesel	Mg	0	3·180	0
Small plant		—	10	0·500	5·00
Site accommodation	8 people unit	Week	10	0·130	1·05
Travel of personnel		Weeks	10	0·355	3·55
Total					41·56

[a]No additional fuel included as this is accounted for in the plant calculations.

Table 3. Construction quantities and associated carbon dioxide emissions for the gabion and regrade remediation option (2 m high gabions and slope of 18·7°) at South Greenford

Item	Component	Unit of component	Quantity	Carbon dioxide: t/ unit of component	Total carbon dioxide: t
Anodes	Mild steel	Mg	2·11	2·700	5·7000
Rebar	Mild steel	Mg	0·29	2·700	0·7800
Grout	Cement	Mg	0·11	0·880	0·1000
Cathodes	Stainless steel	Mg	0·078	6·150	0·4790
Cathodes	Mild steel	Mg	0·035	2·700	0·0945
Cathodes	PVC	Mg	0·235	2·500	0·5880
Wiring [a]	Copper	Mg	0·712	3·010	2·1400
Wiring plastic	PE	Mg	0·096	1·940	0·1860
Fuel [b]	Diesel	Mg	2·78	3·180	8·8400
Small plant		—	2	0·500	1·0000
Site accommodation	4 people unit	Week	10	0·067	0·6700
Travel of personnel		Weeks	5	0·355	1·7800
Total					22·3600

[a]Carbon dioxide associated with the wiring attributed entirely to the project, but in reality it is reused on subsequent projects.
[b]The fuel associated with EKG treatment is included as a separate item over and above fuel associated with the installation plant. This quantity is based on the data recorded from the project where it has been shown that the generator was running at less than its optimum efficiency loading.

Table 4. Construction quantities and associated carbon dioxide emissions for the EKG option at South Greenford

6.4 Ecology and biodiversity

Following a preliminary environmental assessment and site inspection, the Stocks Green site was identified as having medium ecological value, with potential for protected species such as great crested newts and other amphibians and nesting birds in the area. In addition, there was a confirmed presence of dormice and reptiles on the site. Avoiding substantial vegetation clearance helped protect the habitat for nesting birds and the low impact nature of the scheme meant that amphibian exclusion was not necessary. An ecologist was on hand during the works to provide advice where necessary. Similarly, although arboriculture advice was provided to ensure protection of sensitive root protection areas, no tree removal was necessary as the electrode array was adjusted to accommodate the trees (Figure 8).

Figure 8. Installation of EKG electrodes around trees at Stocks Green

The small quantity of scrub that was cleared to allow access helped to increase biodiversity of the embankment by allowing a small amount to light to reach ground level, promoting the growth of under-storey plants and thus improving species diversity and woodland structure. The nature of the works caused only short-term temporary disturbance, which was seen to be of particular benefit to the dormice. One year after the EKG treatment, the dormice had returned to the site.

6.5 Social benefits

The unobtrusive nature of the works meant that no lane closures of the A21 dual carriageway were required and thus no disruption was caused to passing motorists – an advantage rarely seen on traditional embankment stabilisation schemes. Reduced vehicle movements meant less disruption in the form of noise or vibrations for residents on surrounding roads. Likewise, compared to traditional methods, the reduced movements of heavy plant in the EKG scheme resulted in improved air quality for surrounding residents or other

Item	Component	Unit of component	Quantity of component	Carbon dioxide: t/unit of component	Total carbon dioxide: t
Nails	Mild steel	Mg	21·63	2·70	58·40
Face plates	Mild steel	Mg	8·01	2·70	9·47
Grout	Cement	Mg	20·08	0·88	17·67
Geotextile	Polymer	Mg	13·64	0·96	13·10
Fuel	Diesel	Mg	26·64	3·18	84·72
Soil waste [a]	Soil	Mg	11900	—	—
Total					183·36

[a]Carbon dioxide footprint not included as travel distance not known.

Table 5. Construction quantities and associated carbon dioxide emissions for the soil nailing option at Stocks Green

receptors such as pedestrians and cyclists. Furthermore, a low-noise fuel-efficient generator was chosen to ensure both fuel use and noise were kept to a minimum.

6.6 Landscape and visual impacts

In terms of the local landscape, the A21 is located in the Low Weald national character area and the Hildenborough–Leigh Farmlands local character area. The latest assessment for the latter includes specific instruction to create consistent features of standard trees along highways. The EKG scheme ensured this character was not compromised and that local residents' views were maintained entirely. Seven residential properties were located near the failing embankment, the closest of which was immediately adjacent to the works. The visual impacts from conventional methods of embankment stabilisation are significant and even where replanting vegetation is possible it can take a long time for the vegetation to recover to its original condition. A comparison of the visual appearance of the soil nailing repair and the adjacent EKG solution is shown in Figure 9.

7. Discussion

The Highways Agency has identified the EKG method as being cost effective with no waste transport and disposal costs and no substrate purchase and transport costs. The method complies with the requirements of BS 8006 (BSI, 2011) with respect to

Item	Component	Unit of component	Quantity of component	Carbon dioxide: t/unit of component	Total carbon dioxide: t
Anodes	Mild steel	Mg	7·85	2·70	21·20
Rebar and face plates	Mild steel	Mg	2·46	2·70	6·64
Cathodes	Stainless steel	Mg	0·39	6·15	2·37
Cathodes	Mild steel	Mg	0·17	2·70	0·47
Cathodes	PVC	Mg	1·17	2·50	2·91
Wiring [a]	Copper	Mg	2·35	3·01	7·08
Wiring plastic	PE	Mg	0·32	1·94	0·62
Fuel [b]	Diesel	Mg	15·16	3·18	48·22
Fuel (installation)	Diesel	Mg	0·60	3·18	1·90
Grout	Cement	Mg	0·92	0·88	0·81
Total					92·22

[a]Carbon dioxide associated with the wiring is attributed entirely to the project, but in reality it is reused on subsequent projects.
[b]The fuel associated with EKG treatment is included as a separate item over and above fuel associated with the installation plant. This quantity is based on the data recorded from the project where it has been shown that the generator was running at less than its optimum efficiency loading.

Table 6. Construction quantities and associated carbon dioxide emissions for the EKG option at Stocks Green

(a) (b)

Figure 9. Stocks Green: (a) soil nail repair after 2 years; (b) EKG repair after 1 year

design, is fully compatible with Highways Agency policies and good practice for highway schemes (Byron, 2000) and meets the three core elements of sustainability (economic, environmental and social elements). The EKG method

- stabilises a slope
- addresses pore-water pressure changes and provides rapid reductions in pore-water pressures, thus stabilising failing slopes
- addresses shrink–swell behaviour
- reduces maintenance and repair costs
- reduces access requirements for labour, plant and materials
- reduces health and safety risks due to the smaller workforce and less construction activity required
- permits rapid deployment
- permits treatment while maintaining the highway or railway in service without the need for road closures
- provides long-term drainage of a slope through the filtration and drainage functions of the EKGs in passive mode (Figure 10).

Figure 10. Cathode drain providing passive drainage at Stocks Green

Sustainability benefits include reduced carbon dioxide footprint and elimination of the use of primary aggregates. EKG treatment requires fewer HGV movements, zero waste removal, minimal material import, reduced noise and vibrations, improved air quality, preservation of the seed bank and soil environment, minimal vegetation clearance with almost all trees being retained, no visual impacts, no disruption to passing motorists and less damage to root protection areas.

The lower cost and reduced carbon dioxide footprint of EKG treatment are due to the reduced engineering elements associated with the technology compared with other stabilising methods (Table 7) and the ability to provide stabilisation with little environmental disruption (Table 8). In addition, the treatment is gradual, only acts when the current is switched on and does not induce rapid changes in ground conditions (especially settlement). This provides the option to cease treatment immediately if ever it were deemed necessary. The treatment can be flexible in approach by varying the voltage, electrode spacing and duration. Further flexibility is possible by manipulating the electrode array and angle of electrode installation to accommodate in situ obstacles such as trees.

Technique	Excavation and removal of soil	Removal of trees/fauna	Accommodates perched water table	Additional fill	Additional land take	Lane closure	Provides additional drainage	Increased bond of nails	Increased shear strength of soil
Cut off wall	(Yes)	Yes	No	No	n/a	Yes	No	n/a	No
Slacken slope	Yes	Yes	No	Yes	Yes	Yes	No	n/a	No
Toe wall + slacken slope	No	Yes	No	Yes	n/a	Yes	No	n/a	No
Excavate + rock fill	Yes	Yes	Yes	Yes	n/a	Yes	Yes	n/a	No
Excavate + reinforced soil	Yes	Yes	Yes	Yes	n/a	Yes	(Yes)	n/a	No
Soil nailing	Yes	Yes	No	No	n/a	(Yes)	No	No	No
EKG treatment + nails	No	No	Yes	No	n/a	No	Yes	Yes	Yes

Table 7. Comparison of slope maintenance techniques

Technique	Loss of trees, seed bank and soil environment	Production of waste	Importation of fill	Traffic disruption	Increased HGV movements	Increased noise and lower air quality	Threatens habitats and wildlife	Reduction in quality of life	Impact on natural environment
Cut off wall	Yes	(Yes)	(Yes)	Yes	Yes	Short term	Yes	Short term	Yes
Slacken slope	Yes	Yes	No	Yes	Yes	Short term	Yes	Short term	Yes
Toe wall + slacken slope	Yes	Minor	Yes	Yes	Yes	Short term	Yes	Short term	Yes
Excavate + rock fill	Yes	Yes	Yes	Yes	Yes	Short term	Yes	Yes	Yes
Excavate + reinforced soil	Yes	Yes	Yes	Yes	Yes	Short term	Yes	Short term	Yes
Soil nailing	Yes	Yes	No	Yes	Yes	Short term	Yes	Short term	Yes
EKG treatment + nails	No	No	No	No	No	Minor, short term	No	No	No

Table 8. Comparison of environmental and social implications of different maintenance techniques

Acknowledgements

The South Greenford embankment stabilisation was designed by Tony Gee and Partners with Electrokinetic Limited on behalf of Network Rail Western Territory and constructed by Birse Rail. The A21 Stocks Green embankment stabilisation was designed and supervised by a Balfour Beatty Mott MacDonald joint venture with Electrokinetic Limited on behalf of the Highways Agency and constructed by Interserve.

REFERENCES

BSI (2011) BS 8006: Code of practice for strengthened/reinforced soil and other fills: Part 2, soil nails. BSI, London, UK.

Byron H (2000) *Biodiversity and Environmental Impact Assessment: A Good Practice Guide for Road Schemes*. RSPB, WWF-UK, English Nature and the Wildlife Trusts, Sandy, UK.

Casagrande L (1952) Electro-osmotic stabilisation of soils. *Journal of the Boston Society of Civil Engineers ASCE* **39(1)**: 51–83.

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

FHWA (Federal Highway Administration) (1989) *Soil Nailing for Stabilization of Highway Slopes and Excavation*. FHWA, Washington, DC, USA, RD 89-198.

GEO (Geotechnical Engineering Office) (2008) *Geoguide 7: Guide to Soil Nail Design and Construction*. GEO, Hong Kong Special Administrative Region, PRC.

Glendinning S, Loveridge F, Starr-Keddle RE, Bransby MF and Hughes PN (2009a) Role of vegetation in sustainability of infrastructure slopes. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability* **162(2)**: 101–110.

Glendinning S, Hall J and Manning L (2009b) Asset-management strategies for infrastructure embankments. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability* **162(2)**: 111–120.

Highways Agency (2002) *Highways Agency Biodiversity Action Plan*. Highways Agency (currently under review).

Highways Agency (2005) *Customers First; The Highways Agency Corporate Plan*. HA Publication Group, Wetherby, UK, L040062 HA8/05.

Highways Agency (2010) *Business Plan 2010–2011*. HA Design and Publication Services, Dorking, UK, PR/10.

Hughes PN, Glendinning S, Mendes J *et al*. (2009) Full-scale testing to assess climate effects on embankments. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability* **162(2)**: 67–79.

Kilsby C, Glendinning S, Hughes PN, Parkin G and Bransby MF (2009) Climate-change impacts on long-term performance of slopes. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability* **162(2)**: 59–66.

Jones CJFP (2011) Electrokinetic strengthening and repair of slopes. *Geo-Strata ASCE* **15(4)**: 18–26.

Jones CJFP, Lamont-Black J, Glendinning S *et al*. (2008) Recent research and applications in the use of electrokinetic geosynthetics. In *Proceedings of 4th European Geosynthetics Conference, EuroGeo4, Edinburgh, UK* (Dixon N (ed.)). Keynote paper 327.

Lamont-Black J and Weltman A (2010) Electrokinetic strengthening and repair of slopes. *Ground Engineering* **April**: 28–31.

Lamont-Black J, Hall JA, Glendinning S, Jones CJFP and White C (2012) Stabilisation of a railway embankment using electrokinetic geosynthetics. In *Earthworks in Europe* (Radford TA (ed.)). Geological Society, London, UK, Special Publication no. 26, pp. 125–139.

Milligan V (1995) First application of electro-osmosis to improve friction pile capacity — three decades later. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* **113(2)**: 112–116.

Pugh RC (2002) *The Application of Electrokinetic Geosynthetic Materials to Uses in the Construction Industry*. PhD thesis, Newcastle University, Newcastle upon Tyne, UK.