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Innovative Geotechnical Repair Techniques Effectiveness of Electrokinetic Geosynthetics

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1



Executive Summary

Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England (HE). The techniques are the planting of live willow poles, Fibre Reinforced Soil (FRS) and Electrokinetic Geosynthetics (EKG). These techniques were used in place of conventional approaches in order to reduce the overall impact of various challenges including environmental constraints (habitat and visual), access and utility constraints, and to address the need to reduce the scale and/or cost of traffic management and traffic delays.

Trials of the EKG techniques on the Highways England network have been undertaken over the last eight years or so, but post-trial ground investigations and monitoring was generally very limited, or in some cases absent. Post-EKG trial determination of soil parameters is generally not available and longer term evaluation and verification of EKG treatment has not generally been undertaken. This report presents an assessment of the effectiveness of EKG treatment to increase the stability of highway earthworks, and is one of a series for this project.

The use of EKG treatment to aid slope stability has been widely written about and the associated benefits are often described as follows:

- Electroosmotic active dewatering, leading to a reduction in water content, pore water pressures, consolidation and an increase in shear strength.
- Physio-chemical changes in the soil, such as cementation, precipitation, ion exchange and flocculation, which can lead to increases in shear strength, stiffness and a reduction in plasticity.
- Temporary active EKG drainage and permanent passive drainage provided by the EKG cathodes.
- Soil nail reinforcement provided by the EKG anodes with an enhanced soil/nail bond.

Three of the four EKG trials (A21 Stocks Green, M5 Junction 7 and A419 Rat Trap) were undertaken as practical remedial works for known relatively shallow (1m to 2m deep) earthwork embankment instability issues. The fourth EKG trial (A56 Woodcliffe) was undertaken to demonstrate, on a small scale, the effectiveness of EKG primarily for active dewatering of fine grained soils, but also ground improvement.

The lack of adequate post-EKG trial ground investigation, testing and monitoring prevent any clear assessment of the contribution of the various elements of EKG slope stabilisation to be made. A lack of longer term monitoring and verification also hinders the adoption of the EKG treatment to be recommended at the current stage. It was concluded that further EKG trials, building on the lessons learnt, should be undertaken and documented to enable the technique to be taken into more regular use.

Lessons learned from the trials and practical application will need to be incorporated into design guidance and specification in due course, building on the tentative guidance on design and specification issues presented herein.



More generic lessons learnt from the trials and the practical application are reported and these are being combined with those from the reports on FRS and Willow Poles to produce guidance for future Highways England trials of innovative geotechnical repair techniques.

1 Introduction

Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, Fibre Reinforced Soil (FRS) and Electrokinetic Geosynthetics (EKG). These can be used in place of conventional approaches to overcome various issues including environmental constraints (habitat and visual), access and utility constraints, and the need to reduce the scale and/or cost of traffic management and traffic delays.

Trials of the techniques have been undertaken over the last 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken. This report is on the effectiveness of EKG as a repair technique for slope defects and is one of a series for this project.

The use of EKG treatment typically comprises an active treatment phase, when the EKG installation is electrically powered, and a passive phase when the power is switched off. EKG treatment provides four primary contributions to enhance slope stability:

- Electroosmotic active dewatering, leading to a reduction in water content, pore water pressures, consolidation and an increase in shear strength.
- Physio-chemical changes in the soil, such as cementation, precipitation, ion exchange and flocculation, which can lead to increases in shear strength, stiffness and a reduction in plasticity.
- Temporary active EKG drainage and permanent passive drainage provided by the EKG cathodes.
- Soil nail reinforcement provided by the EKG anodes with an enhanced soil / nail bond.

The design of the EKG treatment has been undertaken by Electrokinetic Limited and is based on laboratory testing which is specifically targeted at the EKG technique. The technique is considered to improve the stability of slopes by a number of processes, the contribution of which can be summarised as follows:

- Reduction of pore water pressures by electroosmotic dewatering.
- Reduction in water content due to electroosmotic consolidation.
- Improvements in soil parameters Increase in shear strength.
- Soil/grout Interface shear resistance/adhesion increase around the anode electrode soil nail.

Three of the four EKG trials (A21 Stocks Green, M5 Junction 7 and A419 Rat Trap) were undertaken as practical remedial works for known relatively shallow (1m to 2m deep) earthwork embankment instability issues. The fourth EKG trial (A56 Woodcliffe) was undertaken to demonstrate, on a small scale, the effectiveness of EKG primarily for active dewatering of fine grained soils, but also ground improvement.

To establish the likely performance of the EKG technique a number of tests were undertaken:



- Electrical conductivity tests to BS 1377: 1990 Part 3, to determine that the electrical conductivity is within the treatable range (5 to 50mS/m) suggested by Casagrande (1983) and Mitchell (1993).
- Rosli cell tests (Hamir et al. 2001), to determine coefficients of electroosmotic permeability and consolidation and the rate of consolidation.
- Large EKG Cell tests to determine:
 - Water content.
 - o Atterberg limits.
 - Shear strength.
 - Consolidated drained triaxial parameters.
 - Consolidation settlement.
 - Water discharge.
 - Electrical current during testing.
 - Anode pull out loads.
 - Anode mass loss.

From the laboratory testing, the sites were evaluated for likely electrical power consumption, water discharge and soil material parameter improvements.

The EKG treatment is typically undertaken by drilling or pushing positive (anodes) and negative (cathodes) electrodes into the slope. The electrodes are installed using relatively small drilling rigs which can be customised to enable safe working on slopes (Figure 1).

The anodes consist of 43.5mm outside diameter steel tubes (3.5mm wall thickness) with 6mm diameter drilled holes equally spaced around the circumference at 80mm longitudinal spacings. They are supplied in 1.5m long sections with threaded couplings. Upon completion of the EKG active treatment, the anodes have a 16mm diameter reinforcing bar inserted into the annulus and grouted into place to form a soil nail.

The cathodes consist of 50mm internal diameter slotted uPVC pipes (4.2mm wall thickness), supplied in 1.5m and 3.0m lengths. The pipes have 1mm wide partial circumferential slots at 5mm centres along their lengths. Surrounding the uPVC pipe is a geotextile mesh, geotextile filter and a stainless steel woven mesh, giving the cathodes an overall outside diameter of approximately 66mm.

Power is supplied by a portable generator (typically 80 to 100V) and drainage is installed to collect the electroosmotic water flow during the active treatment phase and the gravity drainage during the passive phase.

The EKG trial applications were focussed on achieving the following benefits over traditional techniques:

- Cost reduction.
- Carbon footprint reduction.



- Traffic management disruption reduced.
- Habitat and environmental disturbance reduced (e.g. habitat conservation at A21 Stocks Green).



Figure 1: P45K slope climbing drill rig on the A21 Stocks Green scheme (BBMM 2014)

Separate reports evaluate the effectiveness of live willow poles (Winter et al. 2018a) and FRS (Seddon et al. 2018). The next stage of the work will draw on the lessons learnt from each of the three techniques in order to provide recommendations and guidance to Highways England for the management of future trials of innovative techniques (Winter et al. 2018b).

Tentative guidance on design and specification issues is presented herein; this is intended to form the basis of more detailed and definitive design guidance and specification information that could follow further trials in due course.





2 Details and Assessment of Trials and Previous Uses

Four trials of the EKG technique undertaken on the Highways England network have been reviewed. The trials on the A21 at Stocks Green (Balfour Beatty Mott MacDonald 2014); the M5 Junction 7 Off-slip (Amey 2014) and the A419 Rat Trap (Elecktrokinetic 2015a; 2015b) were full scale trials of the technique aimed at remediating embankment instability. The A56 Woodcliffe trial (Electrokinetic Ltd 2013) was a field trial to demonstrate (on a small scale) the effectiveness of the technique for treating a relatively deep (6m to 12m) landslide on a large cutting into natural side-long ground.

The four trials were all undertaken and reported by differing organisations. Hence, there is a significant range in the implementation methodology, the focus of the trials, any post-treatment verification testing and any ongoing monitoring.

The key features of the trial sites and the EKG installations at each site are summarised in Table 1.

Site	Installation	Slope	Slope	Slope	Anode	Anode	Cathode	Cathode	Slip Depth	Voltage (V) /	Energy
	Date	height (m)	inclination	aspect	Spacing	Length (m) /	Spacing	Length (m)	(m)	Current (A)	MJ/m ³
		/ length	v:h (°)	(°)	(m)	angle (°) ^{^^^} /	(m)	angle (°) ^{^^^} /			
		(m)			H / S*	No.	H / S*	No.			
A21 Stocks	September	6.5 to 8.5 /	1:2 (27)	E (090)	3.0 / 2.4 to	6.0/20/	3.0 / 5.8	6.0 / -3 / 197	1.5 to 3.0	86 / 713	22.1
Green 1	2011 to	160			2.8	381					
	April 2012										
M5 Junction	February	9.0 to 10.5	1:2 (27)	SE	1.0 to 2.0 /	7.5 / 10 / na	1.0 to 2.0	6.0 / -3 / na	3.0^^	40 to 95 /	na
7	2012 to	/ 265		(135)	2.2 to 2.5		/ 4.4 to			200 to 400	
	July 2012						5.0			(per section)	
A56	January	>75^ / 100	1:2.5 (22)	W	3.0 / 1.2	3.0 to 7.5 /	3.0 / na	15.0 / -3 / 2	6.0 to 12.0	80 / 12 to 35	na
$Woodcliffe^{^+}$	2013 to			(270)		20 / 12					
	February										
	2013										
A419 Rat	October	6.0 / 18	1:2 (27) to	SW	3.0 / 1.0 to	4.5 to 7.5 /	3.0 / 1.0	4.5 to 9.0 /	~ 2m	80 / 140 to	32.6
Trap	2014 to		1:2.5 (22)	(225)	2.0	10 / 28	to 2.0	-3 / 18		50	(lab)
	December										
	2014										

Table 1: Summary features of the EKG trials

* Slope length. ⁺ Trial installation only. [^] Extent of slip scarp. [^] Treatment depth. ^{^^} '-ve' indicates upward inclination.



2.1 A21 Stocks Green 1

2.1.1 Location and Access

The trial is situated approximately 4km north west of Tonbridge at National Grid Reference (NGR) TQ 55570 48050 (555570 148050). It is located on an east-facing embankment slope. Access to the site can be gained from Lower Street at the northern extent of the site or Stocks Green Lane at the southern extent (Figure 2).



Figure 2: Location of the A21 Stocks Green EKG trial. (Image based on OS 1:50000 mapping. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.1.2 Site Details

Geotechnical asset inspections in 2005/6 had identified an approximately 160m length of embankment which had been affected by shallow landslides. There was subsidence of the embankment with tension cracks/scarps up to 1.5m and the formation of hummocky ground (Electrokinetic Ltd 2011a). The embankment is typically 6.5m to 8.5m in height with a slope angle of around 26°.

Investigations by InterRoute (2009) identified soil bulges, dislocated trees and the presence of hydrophilic vegetation. The ground investigation found the ground conditions to be as indicated in Figure 3.



Figure 3: Generalised ground model for A21 Stocks Green (InterRoute 2009)

In 2010, Electrokinetic Ltd was introduced to the scheme and additional ground investigation was undertaken by Concept Site Investigations in February 2011. As part of this work, Balfour Beatty Mott MacDonald (BBMM) commissioned Electrokinetic Ltd to undertake specific electrokinetic geotechnical sampling and testing. Following this BBMM commissioned Electrokinetic Ltd to produce an EKG design report and specification.

Figure 4 shows a typical section through the embankment with shallow slip planes at 1.5m and 3.0m.

The purpose of the repair was to test the principle of retaining the existing slope profile and trees there by limiting the disturbance to the Dormouse habitat that the site provided. The use of a crawler rig accessing the slope from the bottom of the embankment meant that little or no traffic management was required during the works. The reduction in traffic management provided significant cost savings and a major reduction in network / user disruption. The reduction in traffic management also had a positive effect on network user and workforce safety.

The stabilisation of a section of London Underground Ltd (LUL) embankment at Greenford, in the London Borough of Ealing, was undertaken by Electrokinetic Ltd between 4 December 2008 and 19 January 2009 (Lamont-Black 2012). The embankment was approximately 9.0m high with slopes of approximately 22° and composed of a mixture of end-tipped London Clay fill overlying soft clay (Alluvium). The embankment was identified as having a distinct slip surface at approximately 2.5m. A typical EKG electrode configuration was utilised along



with an active treatment period of 42 days. The trial included the use of a hydrated lime anode conditioning treatment.

This trial is of particular interest as post-EKG treatment a ground investigation was undertaken to verify the effect of the EKG treatment on the soils within the embankment. The ground investigation included boreholes with Standard penetration Tests (SPT), in-situ shear vane tests and sampling for laboratory testing.

The results of the post-EKG ground investigation show a distinct improvement in the soil properties, as shown in Table 2. The increase in the plastic limit indicates the significant potential for controlling shrink – swell behaviour of soils.

The trial also demonstrated significant increase in the bond strength of the soil nails (263%) and the effectiveness (>25 time more effective) of the electroosmotic dewatering drains compared to passive drains.

Parameter	Pre-EKG tre	atment	Post-EKG treatment			
	Embankment fill	Alluvium	Embankment fill	Alluvium		
c' peak (kPa)	8	5	18	10		
arphi' peak (°)	25	24	32	26		
Post-peak c' (kPa)	8	3	6	8		
φ' _{res} (°)	19	22	25	22		
PI (%)	49	41	36	39		
Liquid limit	75	66	78	90		
Plastic limit	26	22	42	52		

 Table 2: LUL Greenford trial pre- and post-EKG soil properties (Lamont -Black 2012)

The Electrokinetic Ltd Design for the Stocks Green site was for the site to be split into two treatment panels with the following electrode layout, as shown in Figures 5 and 6:

- Anodes: 6.0m long at 20° below horizontal, horizontal spacing of 3.0m and down slope spacing of 2.4 m to 2.5m.
- Cathodes: 6.0m long at 3° above horizontal, horizontal spacing of 3.0m and down slope spacing of 5.8m.

Late on in the design process, it became apparent that Electrokinetic Ltd would not undertake the design of the electrical elements of the scheme (BBMM 2014) and a specialist electrical designer (Fuseland Ltd) had to be brought in with checks by Mott MacDonald (BBMM 2014).

The EKG anodes and cathodes were installed using Geotechnical Engineering Ltd's P45K slope climbing drill rig (Figure 1). The cathodes were installed in augured boreholes and the majority of the anodes were installed by driving. However, during the initial driving of anodes there were failures of some of the treaded couplings and modifications had to be made to the remaining anodes (BBMM 2014). This involved cutting off the threaded coupler sections and welding on a collar.





Figure 4: Generalised ground model for A21 Stocks Green showing slip planes at 1.5m and 3.0m depth (Electrokinetic Ltd 2011a)

During the EKG treatment there were two small fires due to failure of variacs (variable electrical transformers) which were easily extinguished.

The EKG installation and treatment took place between September 2011 and April 2012, with the active EKG treatment over a 42 day period between 18th November 2011 and 23rd January 2012. The monitoring and verification testing is presented in Section 3.

Figure 7 shows photographs taken before, during and after the works and highlights some of the environmental benefits of the scheme and in particular the rapid recovery of the vegetation cover. The approach to repair at this site was driven by the preservation of topsoil and vegetation, particularly trees, and dormouse habitat; the dormice particularly favour coppiced trees and in Figure 7 a dormouse nesting box is visible. Added bonuses were the lack of a need for traffic management and thus the creation of delays on the network and improved worker safety.



Figure 5: Schematic slope elevation showing the general arrangement of the EKG trial (Electrokinetic Ltd 2011a)



Figure 6: Schematic slope cross section showing the general arrangement of the EKG trial (Electrokinetic Ltd 2011a)





Feb 2011 (pre-construction)



29 September 2011 (start of electrode installation, anode and cathode in foreground)



9 January 2012 (treatment)



13 September 2011 (initial clearance of bramble and dogwood undergrowth)



18 November 2012 (mid treatment)



18 February 2012 (cables removed and anodes converted to reinforcement)

Figure 7: Images showing the time sequence of activities at the A21 Stocks Green site





28 February 2012 (some regrowth, boxes for dormice re-established)



26 April 2012 (regrowth and cathodes acting as passive drains)



03 August 2012 (less than a year after mobilisation)

Figure 7 (Continued): Images showing the time sequence of activities at the A21 Stocks Green site



2.1.3 Slope Inspection

A site inspection was undertaken on 8 March 2017 in dry, overcast weather conditions with good near field visibility, although the inspection ended during rainfall. The site was easily accessed from Lower Street without traffic management.

The slope was predominantly covered in semi-mature trees and brambles with grass and moss covering the ground. Many of the stems of the trees were bent indicating past movement of the slope.

The upper and middle of the embankment were generally concave with a slope angle that varied between 20° to approximately 40° degrees towards the crest, this was considered to represent the old back scar. In the lower parts of the embankment a toe bulge was evident. This and the back scar were considered to be associated with the slope movement prior to installation of the EKG.

Anodes and cathodes were easily identifiable on the slope and, as expected, the spacing between them was variable. The majority of the anodes appeared to have been coated in bitumen and those anodes not coated were corroded. The cathodes were also partially corroded and the majority of them were dry. However, towards the southern end, water was seen flowing from a number of the cathodes indicating that they continued to work as drains. (Figure 8). Corrosion of the anodes/soil nails is an issue that needs further consideration and investigation if large scale EKG repairs are to be taken forward on the HE network in future.



Figure 8: Cathode at A21 Stocks Green. Water flowing from cathode (passive flow)

No signs of recent slope movement were noted on the embankment or on the road above. This indicates that the EKG has been effective preventing further shallow slope movement.



2.2 M5 Junction 7 Off-slip

2.2.1 Location and Access

The trial is situated on the M5 Junction 7 southbound off-slip south-east of Worcester at NGR SO 87700 52400 (387700 252400). It is located on an east-facing embankment slope that supports the southbound off-slip at Junction 7 of the M5. (Figure 9) The embankment is approximately 265m long, between 9m and 11m in height and has an average slope of approximately 26°. Access to the toe of the embankment can be gained from a farm track that joins Whittington Road approximately 20m south of the junction roundabout.



Figure 9: Location of the M5 Junction 7 Southbound Off-slip EKG trial. (Image based on OS 1:50000 mapping. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.2.2 Site Details

This site comprises and embankment which was constructed between 1991 and 1992 as part of the M5 widening scheme. Between 1998 and 2000, WSP had reported three 'shallow rotational slips' on the embankment due to poor fill material and saturation. Attempts to remediate these were undertaken using deep rooted saplings (Electrokinetic Ltd 2011b).

The affected embankment is approximately 265m in length and varying between 9.0m and 10.5m in height with a slope angle of around 26° which had been affected by shallow landslides (Amey 2014). Four areas of the slope contained evidence of pronounced slope failure with clear evidence of tension cracking and hummocking of material (Amey 2014).



The geology at the site is understood to comprise made ground (the embankment) overlying Triassic Mercia Mudstone, with a localised layer of alluvium between the two materials. The embankment fill material is considered to contain reworked Mercia Mudstone and Lower Lias Clay deposits (Electrokinetic Ltd 2011b).

A ground investigation was undertaken in 2010 by Geotechnical Engineering limited and reported in a GIR in 2011 (Amey 2011). This found the ground conditions to be as indicated in Figure 10.



Figure 10: Generalised ground model for M5 Junction 7 based on cross section 2 (Electrokinetic Ltd 2011b)

As part of the EKG design, Electrokinetic undertook a detailed series of slope stability analyses to back analyse the slope failures and to develop the design of an EKG installation. The analyses and resulting EKG trial design are shown in Figures 11 to 13.

The Electrokinetic Ltd Design for the M5 Junction 7 site was for the site to be split into initially two treatment panels. However, during initial stages the two panels were further split to create six panels each 40m to 45m long. The EKG trial used following electrode layout, as shown in Figures 12 and 13:

- Anodes: 7.5m long at 10° below horizontal, horizontal spacing of 1.0m to 2.0m and down slope spacing of 2.2 m to 2.5m.
- Cathodes: 6.0m long at 3° above horizontal, horizontal spacing of 1.0m to 2.0m and down slope spacing of 4.4m to 5.0m.

The EKG anodes and Cathodes were installed using Geotechnical Engineering Ltd's P45K slope climbing drill rig (Figure 1). The Cathodes were installed in augured boreholes and the anodes were installed by driving. (Amey, 2014).





Figure 11: Results of Elecrokinetic (2011b) stability analysis showing postulated failure modes



Figure 12: Schematic slope elevation showing the general arrangement of the EKG trial (Electrokinetic Ltd 2011b)





Figure 13: Schematic slope cross section showing the general arrangement of the EKG trial (Electrokinetic Ltd 2011b)

The EKG installation and treatment took place between February and July 2012, with the active EKG treatment over a 13 week period between around early April 2012 and 9th July 2012. The monitoring and verification testing is presented in Section 3.

2.2.3 Slope Inspection

The site inspection was undertaken on 19 February 2017 in dry, overcast weather conditions with good near field visibility. The site was easily accessed from the farm track that joins Whittington Road, without traffic management.

The slope was predominantly covered in grass, brambles and rushes, with some immatures trees. The ground was wet underfoot, but not boggy.

The slope was relatively uniform in geometry and had slope angles of between 26° and 30°. Terracing was observed and, at the crest of the slope, some minor back scars were noted. These may be an indication of shallow slope movements, although the minor back scars may also be a result of settlement under self-weight of the fill placed as part of the reprofiling works that occurred prior to installation of the EKG. No signs of significant slope deterioration were noted.

Anodes and cathodes were easily identifiable on the slope. The majority of the anodes had galvanised steel face plates which were in reasonable condition. The 16mm steel tendons within the anodes were significantly corroded considering the time since installation. The cathodes tended to display a similar degree of corrosion. Water was noted to be seeping from some of the cathodes indicating that they continued to work as drains. (Figure 14)



No signs of recent slope movement were noted on verge of the off-slip. From the observations, it would appear that the slope is stable with the exception of some creep of the near surface soils. This would indicate that the works were effective in preventing further shallow slope movement, however it is uncertain how much of the improved stability can be attributed to the EKG as the ground was reprofiled prior to installation.



Figure 14: Cathode at M5 Junction 7 Southbound Off-slip. Cathode has water seepage and is significantly corroded



2.3 A56 Woodcliffe Landslide

2.3.1 Location and Access

The trial is situated on the A56 approximately 2km south-south-west of Rawtenstall at SD 79922 20943 (379922 420943). It is located on a west-facing cutting slope (Figure 15). The cutting is between 6m and 20m in height, being approximately 18m high at the location of the trial with a gradient of approximately 24°. Access to the crest of the slope can be gained without traffic management by following a footpath from Bury Road, close to Horncliffe Farm.



Figure 15: Location of the A56 Woodcliffe EKG trial. (Image based on OS 1:50000 mapping. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.3.2 Site Details

The west facing slope of the A56 Woodcliffe Cutting began to fail by landsliding shortly after construction in 1969 (Mott MacDonald 2016a; 2016b). A 100m length of cutting in a natural slope has been affected by deep landslides (Mott MacDonald 2016a and 2016b) which extend some 75m upslope of the highway at an overall slope angle of around 20° (Figure 16).

The movements were first noted in the early 1970s with tension cracks observed along the crest of the cutting slope. Ground investigation during this period identified a slip plane within a sequence of varved (or laminated) clay approx. 6mbgl (Mott MacDonald 2016a; 2016b).



Figure 16; Generalised ground model for A56 Woodcliffe EKG trial (Mott MacDonald 2016a; 2016b).

Herringbone and toe drains were installed in an attempt to improve surface water drainage. In the early 1980s, the toe of the landslide had progressed sufficiently far to cause material to accumulate on the verge adjacent to the southbound carriageway and a 40m length of granular repair was constructed to buttress the slope in this location.

By 1993, the edge of the verge had heaved in the same location and sheet piles were driven into the toe of the original repair to provide additional support (Mott MacDonald 2016a; 2016b). It is understood that these have been successful in preventing material encroaching onto the carriageway in the location of the original failure. However, the toe of the landslide has now reached the back of the safety barrier and the function of the safety barrier has been compromised (Mott MacDonald 2016a; 2016b).

A ground investigation was undertaken in 2011 and inclinometer data identified the location of a major slip plane up to 6 to 12m depth, co-incidental with a horizon of laminated clay. The landslide back scarp is located behind the boundary fence and is approximately 75m away from the toe of the slip, indicating a potential landslide volume of 30,000m³.

An array of surface monitoring pegs was installed in March 2011 and surveyed monthly to record movement across the slope face. These have shown cumulative movements of up to 2.4m at the toe of the landslide over the last four years (in the area immediately north of the retaining wall and where the barrier has been compromised).

In 2012 Electrokinetic Ltd undertook the design of a trial EKG installation to primarily demonstrate, on a small scale, the effectiveness of an active dewatering electrokinetic treatment.

The Electrokinetic Ltd Design for the A56 Woodcliffe trial site was for the following electrode layout, as shown in Figures 17 and 18:



- Anodes: 3.0m to 7.0m long at 20° below horizontal, horizontal spacing of 3.0m and down slope spacing of 1.2m.
- Cathodes: 15.0m long at 3° above horizontal, horizontal spacing of 3.0m with only one cathode per slope treatment section.



Figure 17: Plan showing the general anode and cathode (RD1 and RD2) arrangement of the A56 Woodcliffe EKG trial (Electrokinetic Ltd 2013)

The EKG installation and treatment took place between January 2013 and February 2013, with the active EKG treatment over a 26 day period between 31/01/2013 and 26/02/13. The monitoring and verification testing is presented in Section 3.

The purpose of this trial was to determine whether, at the Woodcliffe site soils, electroosmosis would be effective in drawing water from the soil. Additionally, the trail was aimed at demonstrating the installation and operation of the EKG system on an active landslide with no requirement for traffic management. The reduction in traffic management provided significant cost savings and a major reduction in network/user disruption. The



reduction in traffic management also had a positive effect on network user and workforce safety.



Figure 18: Schematic slope cross section showing the general arrangement of the A56 Woodcliffe EKG trial (Electrokinetic Ltd 2013)

2.3.3 Slope Inspection

Site inspections were undertaken on 6 March 2017 and on 29 August 2018, both in dry, partially overcast weather conditions with good near field visibility. The site was easily accessed from the crest via a footpath that joins Bury Road near Horncliff Farm. The path and the field above the cutting were wet and boggy with abundant hydrophilic vegetation. A significant graben feature, some 10m to 15m across, was observed in the field above the cutting.

The slope in the vicinity of the trial was predominantly covered in grass with some semi matures trees. The ground was soft underfoot and in places wet, but not boggy.

The slope had a stepped geometry formed by a series of back scarps and toe bulges associated with the continued slope instability (Figure 19). Similar slope geometry and indications of slope movement were evident along the length of the cutting.

Anodes and cathodes were observed on the slope. The anodes and the 16mm steel tendons were corroded. No face plates had been installed on the anodes. The cathodes tended to display a similar degree of corrosion. No flow of water was observed from the cathodes during the two site inspections.

As previously noted, the trial was to determine whether, in the Woodcliffe site soils, electroosmosis would be effective in drawing water from the soil, thus as EKG treatment was not active during the site inspections no comment on the effectiveness can be made. However, the trial monitoring data in Section 3.3 confirms the effectiveness of the EKG treatment at the Woodcliffe site.





Figure 19: A56 Woodcliffe cutting in vicinity of the EKG trial (Site Photograph 7DW_4145)



2.4 A419 DBFO Rat Trap

2.4.1 Location and Access

The trial is situated on the A419 north-north-east of Swindon at SU 17592 87908 (417592 187908). It is located on a south-west-facing embankment slope (Figure 20). Access to the toe of the slope can be gained without traffic management via a footpath which runs along the toe from the A419 / A361 / B4006 roundabout.



Figure 20: Location of the A491 Rat Trap EKG trial. (Image based on OS 1:25,0000 mapping. Reproduced by permission of Ordnance Survey, on behalf of HMSO, © Crown copyright and database rights, 2018. All rights reserved. Ordnance Survey Licence number 100030649

2.4.2 Site Details

The south west facing embankment of the A419, adjacent to the north west bound carriageway, developed a tension crack on the slope side of the vehicle restraint barrier (VRB) (WSP 2012; EKG 2015a). A 15m length of embankment was affected (EKG 2015b) with a 'slip plane' having been noted extending from the crest to approximately 2m above the toe (EKG 2015a). The embankment is approximately 6.0m high and is generally at an angle of 22°, locally up to 27° (WSP 2012) (Figure 21).



Investigations by WSP in 2011 (WSP 2012) indicated that there was evidence of a '...shallow rotational failure (distinct backscarp, slope bulging...' and undermining of the Vehicle Restraint Barrier (VRB). The VRB was moved closer to the carriageway and a CCTV survey of a carrier drain located at the crest of the slope was undertaken. The CCTV survey revealed severe cracking in the drain and this was subsequently replaced (WSP 2012).

A ground investigation was undertaken by WSP in 2011 (WSP 2012) and this revealed the road embankment was constructed upon very soft alluvium overlying interbedded stiff to very stiff sandy clays and stiff silts of the Jurassic Age Corallian Group strata. The investigation indicated that the embankment was constructed of cohesive fill (reworked clay) overlain by varying thickness of granular fill (Type 1 sub- base material). The ground conditions are shown in Figure 21.



Figure 21: Generalised ground model for the A419 (Electrokinetic Ltd 2015a)

As part of the EKG design, Electrokinetic Ltd undertook a detailed series of slope stability analyses to back analyse the slope failure and to develop the design of an EKG installation. Examples of the analyses and resulting EKG trial design are shown in Figures 22 to 24.

The Electrokinetic Ltd Design for the A419 Rat Trap was to treat an 18m long section of the embankment. The EKG trial used following electrode layout, as shown in Figures 23 and 24:

- Anodes: 4.5m to 7.0m long at 10° below horizontal, horizontal spacing of 3.0m and down slope spacing around 1.0m to 2.0m.
- Cathodes: 4.5m to 9.0m long at 3° above horizontal, horizontal spacing of 3.0m and down slope spacing of around 1.0m to 2.0m.



The EKG anodes and Cathodes were installed using the Geotechnical Engineering Ltd P45K slope climbing drill rig (Figure 25). The Cathodes were installed in augured boreholes and the anodes were installed by driving. (Electrokinetic Ltd 2015b).

Analysis No.	Description	FoS	Sketch	Comment
1	Back analysis of current profile	0.96	120- x	The failure surface matches the description in the GIR with the top daylighting at the crest and the bottom daylighting approximately 2m from the toe
2	EK improved parameters for cohesive fill material and EKG reinforcement (BS8006:2- 2011 partial factor set 2). Back analysed failure	1.12	115 115 106 Cohesive II Cohesive II Coh	Addition of EKG reinforcement and improvement of shear strength parameters stabilises back analysed failure surface

Figure 22: Results of Electrokinetic Ltd (2015a) stability analysis showing postulated failure mode



Anode Column Cathode	1		2		3		4		5		6		7	
Column		1		2		3		4		5		6		Croct
Anode	1.	.5m		3.0m										- orest
row	×	\rightarrow	×		\rightarrow		×		×		×		×	Cathode row
в	×	0	×	0	×	0	×	0	×	0	×	0	×	A
С	×	0	×	0	×	0	×	0	×	0	×	0	×	В
D	×	0	×	0	×	0	×	0	×	0	×	0	×	С
														— Toe
		0	Cath	ode										
		×	Anoc	le										





Figure 24: Schematic slope cross section showing the general arrangement of the EKG trial (Electrokinetic Ltd 2015a)





Figure 25: The P45 Slope climbing drill rig installing electrodes (Electrokinetic Ltd 2015b)



Figure 26: AC generator, fuel tank, DC power supply, electrode connections and security mast for the EKG treatment (Electrokinetic Ltd 2015b)

The EKG installation (Figure 26) and treatment took place between October and December 2014, with the active EKG treatment over a 6 week period between 30th October 2014 and 11th December 2014. The monitoring and verification testing is presented in Section 3.4.



2.4.3 Slope Inspection

At the A419 Rat Trap the approach embankment to the bridge on the north-west bound carriageway was reported as having a scarp at the crest of the slope and the exit plane of a slip, or a bulge, approximately 2m above the toe. This was interpreted as a shallow slide in the face of the embankment and was, at least in part, attributed to leaking drainage behind the crest of the slope. The drain was repaired prior to the progression of the design and execution of an EKG remediation scheme.

The inspection carried out by the project team in January 2018 revealed both a break in slope, approximately 2m above the toe, in the area immediately to the south-east and a separation between the concrete barrier-post foundations and the embankment materials above the remediation (Figure 27). This separation was approximately 50mm to 100mm wide and was able to be probed with a rule to a maximum of 500mm and 800mm. This separation extended approximately 4m or more from the abutment wing wall. It is not clear whether this separation was evident prior to the EKG remediation, and is thus the scarp that was referred to in the ground investigation, or whether it has developed since the remediation was carried out; in the latter case this could be due to the drying out of the treated material, for example.



Figure 27: Separation crack between the slope materials and concrete barrier-post foundations (January 2018)


The interpretation of the existence of a shallow slide seems to be questionable. This is not only due to the existence of the observed separation described above but also due to other factors. The break in slope observed in January 2018 to the south-east of the remediation is coincident with the reported pre-remediation 'exit plane' and strongly resembles a construction artefact. In addition, despite being specifically intended to locate the hypothesised slip plane this was not observed in the trial pits opened during the ground investigation. Similarly, no evidence of a slip plane was found from the window sampling undertaken.

In this context there exists considerable uncertainty surrounding questions as to whether

- the initial drainage repair was sufficient to remediate the problem (the ground investigation specifically identifies the drain as the primary cause of the supposed failure),
- the slide that the EKG was designed and executed in order to remediate did indeed exist, and therefore
- the EKG remediation was required.

This is compounded the lack of inspection data lodged in HAGDMS, not just for the site but for the A419 as a whole. This is further reflected by the apparent failure to follow the correct geotechnical procedures set out in HD22 and HD41 of the DMRB, which are designed to *inter alia* ensure that provisional interpretations are questioned and tested against alternative plausible hypothesise.

This failure to follow geotechnical procedures is also mirrored in two other EKG remediation sites on the A14 at Junction 33 Westbound and, also on the A14, at MP102/2. In the case of the Junction 33 site the EKG remediation was aborted when the materials were found to be more competent than was originally anticipated. In short, the remediation was not necessary; a fact that would have been clear prior to mobilisation and, indeed, design, if an appropriate ground investigation had been conducted and the geotechnical procedures followed.



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3 Testing and Monitoring Results

Each of the three sites (A21, M5 and A56) had been subject to extensive site investigation and monitoring prior to the EKG trials (BBMM 2014; Amey 2014; and Mott MacDonald 2016a & 2016b respectively). The testing and monitoring for each site varied considerably both during and following the EKG trials and are described individually for each trial below.

3.1 A21 Stocks Green 1

For the A21 trial, there are geotechnical soil parameters from the 2009 ground investigation prior to the EKG trial (BBMM 2014), but the only other investigation and testing is the EKG ground investigation (2011), sampling and laboratory testing prior to the trial, from the Rosli Cell and Large Cell tests (BBMM 2014 and Electrokinetic Ltd 2011). These tests provide laboratory post-treatment parameters. No post-EKG site verification testing of the soils was undertaken.

Table 3 provides a summary of the ground investigation, testing and monitoring for the site.

Item	Problem investigation	During EKG trial	Short-term (weeks) post- EKG	Long-term (years) post- EKG
Intrusive ground investigation	\checkmark	x	×	?
In-situ testing	\checkmark	×	×	?
Laboratory testing	\checkmark	\checkmark	x	?
Groundwater monitoring	\checkmark	 ✓ recommend improvement 	 ✓ recommend improvement 	?
Movement monitoring	\checkmark	\checkmark	\checkmark	?
EKG laboratory testing	na	\checkmark	na	na
Chemical testing	×	×	×	×

Table 3: A21 Stocks Green summary of ground investigation, testing and monitoring

Table 4 presents the relevant soil parameters for the A21 Stocks Green site prior to EKG treatment and also post-laboratory scale EKG trials in the Rosli Cell and the Large Cell.

Soil testing from the laboratory testing work indicates the following ground improvement changes due to EKG treatment:

%.
%

Plasticity Index PI: reduced by 0% to 6%.

Drained Friction Angle ϕ' : increased by 1° to 2°.



Drained Cohesion c':

increased by 3kPa to 4kPa from Rosli cell versus 4kPa to 8kPa from Large Cell test.

Parameter	A21Stocks Green			
	Coil	Pre-EKG	Post-EKG	
	5011	laboratory test	laboratory test	
Water Content w (%)	MG(i)	23	21	
	MG(ii)	24	19	
	MG(iii)	28	24	
Plastic Index PI (%)	MG(i)	31	25	
	MG(ii)	29	24	
	MG(iii)	26	26	
	MG(iii)	26	22	
	MG(iii)	26	24	
Undrained shear strength cu pk/res	MG(i)	57/35	140/40	
(kPa) - from Large Cell Test - Hand Shear	MG(ii)	96/36	>140*	
Vane	MG(iii)	72/28	>140*	
	MG(iii)	140/42	>140*	
	MG(iii)	130/na	128/35	
Friction angle φ' pk (°)	MG(i)	21	23 / 30	
xx / xx represents results of Rosli Cell /	MG(ii)	24	25 / 27	
Large cell - CDTT	MG(iii)	24	25 / 25	
Cohesion c' (kPa)	MG(i)	1	5/9	
xx / xx represents results of Rosli Cell /	MG(ii)	2	5/8	
Large cell - CDTT	MG(iii)	2	5/6	
Cu (kPa) - Hand Shear Vane	MG(i)	30	60	
	MG(ii)	50	60	
	MG(iii)	75	80	
Pull out (kN/m) / Adhesion (kPa) /	MG(i)		3.8/10.3/26	
Interface Shear (kPa)	MG(ii)	na	7.4 / 34.7 / 52	
	MG(iii)		10.3 / 54.7 / 72	
	MG (iii) Control		3.9 / 8.5 / 28	

Table 4: Pre- and post-EKG geotechnical soil parameters

Notes:

* Max value on shear vane.

MG = Made Ground.

Following Large Cell tests, the anode 'soil nails' were subjected to pull-out tests, the results are shown in Table 4. Comparison of the MG(iii) EKG treated and the MG(iii) Control indicate a significant increase in the Pull-out load, Interface Shear Resistance and the Adhesion which has been attributed to the formation, over 15 days, of a cemented zone ('halo') extending 35mm to 40mm radially out from around the anode (Figure 28).





Figure 28: Development of a zone of increased adhesion immediately around the anode in the large cell laboratory test (Electrokinetic Ltd 2013)



Figure 29: Plot of interface shear resistance against extension for the large cell anode pullout tests (Electrokinetic Ltd 2013)



Figure 29 shows the shear resistance of the anode pull-out tests against extension. These plots indicated that, other than the MG(i) soil, the EKG tests have created a strong peak shear resistance. Of particular note is the improvement of shear strength of MG(iii) following EKG treatment compared to the MG(iii) Control. The EKG treatment had created a brittle bond.

The testing also indicated that the EKG soil nail bond / adhesion was a function of the electrical current passed and that, to ensure this is optimised, logging of the electrical current demand should be undertaken.

Six anode soil nails were selected for pull-out testing to confirm that the soil nails met the required design verification load of either 33kN or 50kN (in practice all soil nails were tested to 50kN). Figure 30 shows the testing equipment and set up. BBMM (2014) recommended that for future trials more sacrificial EKG soil nails and conventional control soil nails are installed.



Figure 30: Soil nail testing equipment and set up (after Electrokinetic Ltd 2013)

Borehole groundwater monitoring standpipes were monitored before, during and after the EKG trial but the majority were dry immediately prior to, during and following the trial (BBMM 2014). BBMM (2014) recommended that for future work that data logged piezometers are installed to monitor trials.

Following installation of the EKG cathodes in the southern area on the 10th October 2011 there was no flow of water until active EKG treatment commenced on 18th November 2011. Once EKG active treatment commenced, water started to flow from the cathodes after a period of between 24 hours and 48 hours. The active EKG treatment yielded approximately 5,400l of water over approximately 42 days.

The collection and monitoring of water was undertaken using plastic bags attached to the proximal ends of the cathodes. The water discharge monitoring was undertaken manually



by emptying these bags, and this required the EKG power to be turned off. BBMM (2014) recommend that flat hose drainage down to the toe collection drain should be installed.

The EKG trial had a duration of 42 days. Figure 31 shows the current draw between 11 and 23 January 2012. This gives an average current draw of 713A (when the initial peak values are discounted) with a voltage of 86V (BBMM 2014). The EKG trial treated 10,080m³ of soil resulting in an energy consumption of 22.1MJ/m³ of soil, which was in good agreement with the predicted values from the Electrokinetic Ltd (2011a) Geotechnical Design Report.

The Electrokinetic Ltd (2011a) Geotechnical Design Report estimated the current demand as 3 amps per metre. However, during the trial the actual demand was approximately one third of this (BBMM, 2014). Based on this, BBMM (2013) recommended that for future applications of EKG the initial ground investigations could include the following to obtain a better pre-trial estimate of current draw and enable cost savings to be made with regards to the electrical installations:

- Electrical resistance testing across the site and the use of prescriptive anodes.
- Larger number of Large Cell tests due to the amount of soil required for these (30kg plus for each test) they recommend pushing the test cylinders into trial pits to obtain the samples.

BBMM (2014) recommend that, for better monitoring and control over the electrical supply, having separate treatment panels and circuits with shunt resistors to enable data logging of the electrical supply.







The inclinometers were monitored before, during and following the EKG trial. Borehole 3 indicated the largest movement with:

- Before trial (pre-EKG) movement 0.6cm upslope.
- During EKG treatment movement 0.4cm up slope followed by 1.6cm of down slope.
- Post-EKG treatment movement 1.6cm down slope followed by 0.3cm up slope.

This gives an overall movement of 1.9cm downslope.

3.2 M5 Junction 7 Off-slip

For the M5 Junction 7 EKG trial, there were geotechnical soil parameters recorded from the 2010 investigations before the EKG trial (Amey 2014), and a post-EKG site verification ground investigation in 2012. This comprised three dynamic sampler boreholes and four hand held percussive holes (depths between 1.75m and 5.20m) from which post-EKG trial soil parameters were derived (Amey, 2014). It is understood that in 2014 a further two windows sample holes and six Cone Penetration Tests (CPT) were undertaken but records have not been seen.

Table 5 provides a summary of the ground investigation, testing and monitoring for the site.

Item	Problem investigation	During EKG trial	Short-term (weeks) post- EKG	Long-term (years) post- EKG
Intrusive ground investigation	\checkmark	×	\checkmark	?
In situ testing	2	×	×	?
	I	~	^	2014
Laboratory testing	1	1	/	?
	v	v	v	2014
Groundwater monitoring	\checkmark	 ✓ water potential installations 	?	?
Movement monitoring	?	✓ crest survey	?	?
EKG laboratory testing	na	✓	na	na
Chemical testing	×	×	×	×

Table 5: M5 Junction 7 Off-sli	p summary o	f ground investigat	ion. testing and mon	itoring
		Biodina miteotigat		

Table 6 presents the relevant soil parameters for the M5 Junction 7 site prior to EKG treatment and also the post -EKG site trial. Consolidated undrained triaxial tests were inconclusive (Amey 2014) and are not included.

Soil testing from the verification ground investigation work indicated the following ground improvement changes due to EKG treatment:

Water Content w:	reduced by 5%.
Plasticity Index PI:	reduced by 3% to 4%.
Liquid Limit LL:	reduced by 3% to 5%.

Figure 32 is a plot of water content against plasticity index which demonstrates that the EKG treatment had reduced the water content to significantly below the plasticity index.



Amey (2014) recommended that post-EKG trial verification ground investigation and testing should be undertaken one year after the trial to verify the effectiveness of the treatment in improving soil strength properties. They recommended triaxial testing of soil samples and in situ testing, such as Cone Penetration Tests (CPT).

Parameter	M5 Junction 7		
	Soil	Pre-EKG	Post-EKG laboratory
	501	laboratory test	test
Water Content w (%)	RMM	24	19.0
	RLC	19.5	14.6
Plastic Limit PI (%)	RMM		
	RLC		
Liquid Limit LL (%)	RMM	24	20.2
	RLC	19.5	14.6
Undrained shear strength Cu min.,	RMM	22.7 / 48.1 / 87.0	≥ 140* / ≥ 140* / ≥ 140*
mean & max (kPa) -– Laboratory Shear	RLC	25.9 / 41.3 / 72.2	40.0 / 40.0 / 40.0
Vane			
Maximum Pull out load (kN) / Pullout	na	na	22 / 2.93
load per m (kN/m)			23 / 3.07
			31 / 4.13
			28 / 3.73
			28 / 3.73
			14.5 / 1.93
			46 / 6.13
			46 / 6.13
			40.3 / 5.37

Table 6: Pre- and post-EKG geotechnical soil parameters

Notes:

* Max value on shear vane.

RMM = Reworked Mercia Mudstone and RLC = Reworked Lias Clay.

Three anode soil nails were selected for pull-out testing to confirm that the soil nails met the required design working load of 26.4kN. Two of the nails failed the test and a further six additional nails were tested, of which five passed the test and one failed. The failure of the nails was attributed to a possible combination of extremely wet conditions, stiff material in the embankment core and installation methods. The driving head of the anodes was slightly larger in diameter than the main anode, thus potentially reducing the bond along the nail length. Also, some of the nails were rotated when removing the top section of the anode to convert them to soil nails (Amey 2014).

Amey (2014) also observed corrosion of the EKG soil nails and heads and this observation is further reinforced by site observations in 2017. Corrosion of the anodes/soil nails is an issue that needs further consideration and investigation if large scale EKG repairs are to be taken forward on the HE network in future.

Based on the soil nail pull-out loads of 14.5kN to 46kN, a mean value of 31kN, yielding an adhesion of 25kPa, was adopted for assessment of the slope stability. The slope stability analysis was undertaken with an EKG improved fill as shown in Figure 33. As post-EKG shear strength data was unclear (Electrokinetic Ltd 2014), a c' value of 3kPa was used. The



analysis indicated that the failure surfaces been pushed back deeper into the slope and had a satisfactory factor of safety of greater than 1.3 (Figure 33)



Figure 32: Plot of moisture content in relation to plastic limit before and after EKG treatment (after Electrokinetic Ltd 2014)



Figure 33: Slope stability analysis following EKG treatment showing failure surface driven deeper and having a satisfactory factor of safety (>1.3) (after Electrokinetic Ltd 2014)

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Unfortunately, the preparation works for the EKG treatment included the excavation and benching of the slope, apparently for safety reasons, as shown in Figure 34. Comparing the benched excavation (Figure 34) with the slope stability analysis (Figure 33) and with the effective depth of EKG treatment in Figure 35 indicates that the toe of the original slip planes is likely to have been dug out and replaced and that much of the material treated by EKG was replaced material.

Figures 36 and 37 show the water discharge and rainfall for cathode X14 Row E against time. Over the duration of the EKG treatment, this cathode discharged 132l of water which represents a flow of 6.6l/day with electroosmotic flow. By comparison with only passive hydraulic drainage, the same electrode discharged only 2l of water prior to EKG treatment, giving a flow rate of 0.05l/day. Electroosmotic enhanced discharge is approximately 130 times the passive hydraulic discharge.

The collection and monitoring of water discharge was undertaken using plastic bags attached to the proximal ends of the cathodes. The water discharge monitoring was undertaken manually by emptying these bags. This required the EKG power to be turned off. Hence Amey (2014) recommend that flat hose drainage down to the toe collection tank should be installed. Amey (2014) also reported the high pH of the discharge water and the possible health and safety issues associated with this.

Figure 38 shows the water discharge, rainfall and the current demand for cathode X14 Row E against time. This indicated that the current and the water discharge closely followed rainfall events indicating direct hydraulic connectivity with the recharge source.

Of the four water monitoring standpipes installed during the 2010 ground investigation, only one survived the site reprofiling and EKG installation works. The installation WS11 was dry at the start of the EKG trial.

Two dielectric water potential sensors were used to monitor water potential and temperature during and immediately (approximately six weeks) after the trial. Monitoring of electrical parameters was undertaken. An example monitoring plot is shown in Figure 39, which shows that during active EKG treatment both the shallow and deep sensors indicated wet conditions (water potential close to zero) and that following treatment the sensors showed the soil drying out.

The EKG trial had a duration of 13 weeks between around early April 2012 and 9th July 2012. Figure 40 shows the current draw between 20th June 2012 and 9th July 2012 and Figure 31 shows the current draw over the full period.

The typical electrical demand for each EKG trial section was 40V to 95V with a current draw of 200A to 400A. Amey (2014) recommend that having separate treatment panels and circuits, with shunt resistors to enable data logging of the electrical supply, would be an improvement for future EKG trials.





Figure 34: Figure from the Amey (2014) GFR showing the depth of the slope reprofiling



Figure 35: Figure from the Amey (2014) GFR showing the effective depth of EKG treatment





Figure 36: Plot of water discharge from cathode and rainfall against time for Row E cathode during and post-EKG treatment (after Electrokinetic Ltd 2014)



Figure 37: Plot of cumulative water discharge from cathode and rainfall against time for Row E cathode during and post-EKG treatment (after Electrokinetic Ltd 2014)





Figure 38: Plot of water discharge from cathode, current draw and rainfall against time for Row E cathode during and post-EKG treatment (after Electrokinetic Ltd 2014)



Figure 39: Plot of water potential against time for Row E cathode (after Electrokinetic Ltd 2014)





Figure 40: Current and voltage variation for treatment duration (after Electrokinetic Ltd 2014)



3.3 A56 Woodcliffe Landslide

For the A56 EKG tria, I geotechnical soil parameters from before the EKG trial are available (Mott MacDonald 2016a; 2016b). No post-EKG site verification soil testing was undertaken, however three pull-out tests were undertaken on anode soil nails.

Table 7 provides a summary of the ground investigation, testing and monitoring for the site.

Item	Problem investigation	During EKG trial	Short-term (weeks) post- EKG	Long-term (years) post- EKG
Intrusive ground investigation	\checkmark	×	×	?
In situ testing	\checkmark	×	×	?
Laboratory testing	\checkmark	×	×	?
Groundwater monitoring	\checkmark	\checkmark	\checkmark	?
Movement monitoring	\checkmark	×	?	?
EKG laboratory testing	na	×	na	na
Chemical testing	×	\checkmark	x	×

Table 7: A56 Woodcliff summary of ground investigation, testing and monitoring

Three anode soil nails were selected for pull-out testing to confirm the available ultimate anode to soil bond strength. The testing yielded bond capacities of 5.0, 9.3 and 12.5 kN/m length of anode soil nail.

Data logged water discharge monitoring of the cathode drains was undertaken prior to (19 weeks), during (4 weeks) and after (5 weeks) the EKG treatment (Figures 41 and 42).

Figures 41 and 42 demonstrate the significant increase in water discharge from the cathode drains during the active EKG treatment when compared to the initial passive drainage. The data indicated a passive discharge of 329l over a 19 week period followed by an EKG treatment discharge of 1173l over a 4 week period. This gives an approximately 17 times greater flow rate, due to the higher electroosmotic permeability and electrical potential gradient when compared to the hydraulic permeability and gradient.

Monitoring of electrical parameters was undertaken and indicated an applied voltage of 80V with a resulting average current of 23.5A (range 12A to 35A), as shown in Figure 41. This represents a power consumption of around 4,200MJ (Mega Joules).

The discharge water was subject to a suite of chemical tests during the EKG treatment as shown in Figure 43.



Figure 41: Plot showing EKG current draw against water discharge from the cathode during the 4 week trial (after Electrokinetic Ltd 2013)



Figure 42: Plot showing the discharge from the cathode during the initial passive phase, during EKG treatment and following treatment (after Electrokinetic Ltd 2013)

Figure 43 indicates that the discharge from the cathode has a high pH and increased levels of various compounds, particularly Chloride and Sulphate (as SO₄).

The A56 site has borehole inclinometer monitoring data from before the trial and groundwater level monitoring data from before, during and after (5 weeks) the trial (Mott MacDonald 2016a; 2016b). The borehole inclinometer monitoring data showed movement of between 0.1m and 0.4m along a major slip plane at 6m to 12m depth which is associated with a laminated clay (Mott MacDonald 2016a). The groundwater monitoring data from data logged piezometers in boreholes BH10, BH11 and BH12 are presented in Figures 44 to 46 respectively along with rainfall data.



			Lab No.	490952	490953	490954
		S	ample ID	Active Cathode Discharge	Cathode	Control
			Depth			
		Sa	mple Ref	P1213	P1213	P1213
		Sam	ple Type	EW	EW	EW
		Samp	ling Date	26/02/2013	04/02/2013	04/02/2013
		Sampl	ing Time			
Test	Units	DETSxx	LOD			
Calcium, Dissolved	mg/l	DETSC 2306	0.09	600	910	21
Magnesium, Dissolved	mg/l	DETSC 2306	0.02	0.05	0.02	2.2
Potassium, Dissolved	mg/l	DETSC 2306	0.08	260	37	1.6
Sodium, Dissolved	mg/l	DETSC 2306	0.07	5 1 0	170	9.7
Alkalinity as CaCO3 (Automated)	mg/l	DETS 030	10	2000	1600	70
Chloride	mg/l	DETSC 2055	0.1	88	14	15
Nitrate as N	mg/l	*	0.1	< 0.10	< 0.10	< 0.10
Ortho Phosphate as P	mg/l	DETSC 2205	0.01	< 0.01	< 0.01	< 0.01
Sulphate as SO4	mg/l	DETSC 2055	0.1	330	39	6.6
Conductivity	uS/cm	DETSC 2009	1	14000	11100	1940
Ammoniacal Nitrogen as N	mg/l	DETSC 2207	0.015	2.5	2.7	< 0.015
pH		DETSC 2008		13.0	13.0	9.4

Figure 43: Summary of chemical analysis of cathode discharge water (after Electrokinetic Ltd 2013)



Figure 44: Plot of BH10 groundwater level against date and time (after Electrokinetic Ltd 2013)





Figure 45: Plot of BH11 groundwater level against date and time (after Electrokinetic Ltd 2013)



Figure 46: Plot of BH12 groundwater level against date and time. (after Electrokinetic Ltd 2013)



Table 8 presents a summary of the groundwater levels from the monitoring boreholes. The data indicated that BH10 shows a slight lag in the response to EKG treatment when compared to the other boreholes.

BH10 showed rapid and large amplitude responses to rainfall events, which may be due to it being in an area with tension cracks causing it to be in better connectivity with surface rainwater (Electrokinetic Ltd 2013). This may also help to explain what appears to be a rapid recovery to near pre-EKG trial water levels.

BH11 and BH12 showed some recovery of water levels, though they were not 'peaky' like BH10, possibly for the above reason. The post-EKG monitoring lacked any rainfall data for comparison and only continued for five weeks after the end of the EKG trial.

Table 8: Summary of groundwater levels and their change prior to, during and after theEKG trial

	A56 Woodcliffe Ground Water Level (mAOD) / change from initial level (m)				
Borehole	Pre-EKG trial	End EKG trial	5 weeks post-EKG trial		
BH10	178.5	177.3 / -1.2	178.0 / -0.5		
BH11	177.0	175.0 / -2.0	175.6 / -1.4		
BH12	175.7	175.0 / -0.7	175.3 / -0.2		

3.4 A419 Rat Trap

For the A419 trial, there are geotechnical soil parameters from the 2011 ground investigation prior to the EKG trial (WSP 2012), but the only other investigation and testing is the EKG ground investigation, sampling and laboratory testing prior to the trial, (Electrokinetic Ltd 2015a). These tests provide laboratory post-EKG treatment parameters. No post-EKG site verification testing of the soils was undertaken.

Table 9 provides a summary of the ground investigation, testing and monitoring for the site.

ltem	Problem investigation	During EKG trial	Short-term (weeks) post- EKG	Long-term (years) post- EKG
Intrusive ground investigation	\checkmark	✓ trial pits	×	x
In-situ testing	\checkmark	×	×	×
Laboratory testing	\checkmark	✓ limited	×	×
Groundwater monitoring	 ✓ only at toe of embankment 	×	×	x
Movement monitoring	×	×	×	x
EKG laboratory testing	na	\checkmark	na	na
Chemical testing	\checkmark	×	×	x

Table 9: A419 Rat Trap summary of ground investigation, testing and monitoring

Table 10 presents the soil parameters for the cohesive embankment fill at the A419 Rat Trap site prior to EKG treatment and also post-laboratory scale EKG trials in the Rosli Cell and the Large Cell.

Given the limited testing information available and the issues identified in the Electrokinetic Ltd (2015b) report (see note on Table 10) the improvement in the strength of the cohesive soil fill due to the EKG laboratory treatment is not clear.

Following EKG Large Cell tests, the anode 'soil nails' were subjected to pull-out tests at zero five and fourteen days (Electrokinetic Ltd 2015a). The results are shown in Fig 47. Table 10 and Figure 47 show that there is a clear improvement in the interface shear strength for the soil nails of between 17.7% (five days) and 41.5% (fourteen days).

The testing also indicated that the soil had started to 'shrink away' from the Anode during the testing, indicating a state of negligible normal stress acting upon the Anode (Electrokinetic Ltd 2015a). This indicates that the interface shear strength is primarily due to adhesion (Electrokinetic Ltd 2015a).

Parameter	A419 Rat Trap		
	Pre-EKG laboratory	Post-EKG	
	test	laboratory test	
Bulk Density (kN/m³)	21.0	Na	
Water Content w (%)	25 to 32	Na	
Plastic Index PI (%)	27 to 38	Na	
Hydraulic Permeability k _h (m/s)	5.89 x 10 ⁻¹¹	Na	
Electroosmotic Permeability k _e (m/s)	2.19 to 2.51 x 10 ⁻⁷	Na	
Undrained shear strength cu pk/res	50@ <1.0m depth	Na	
(kPa)	75@ >1.0m depth		
Friction angle ϕ' peak (°)	16 (25)*	25.5	
Cohesion c' (kPa)	9.5 (0.0)*	4.0	
Interface Shear (kPa) / Adhesion (kPa)	27.13	31.23 to 38.39	

Note: * Values obtained from testing did not produce a failure surface which matched that conjectured for the site. Hence, WSP (2012) values used.



Figure 47: Plot of interface shear resistance against extension for the large cell anode pullout tests (Electrokinetic Ltd 2015a)

Following the EKG treatment on site, three anode soil nails were selected for pull-out testing to confirm that the soil nails met the required design verification loads of:

- Column 3, Row A 7.3kN.
- Column 3, Row B 9.7kN.
- Column 5, Row C 13.5kN.

For design loads and anode locations see Electrokinetic Ltd (2015a) and Figure 23. The results of the testing are shown in Figure 48.



The only groundwater monitoring reported for the A419 site was from the WSP 2011 ground investigation (WSP 2012), which indicated that the groundwater levels monitored in four windows sample holes in July 2012 varied from 0.39m to 0.66m below ground level. There are no known records of groundwater monitoring or flow of water from the Cathodes during the EKG treatment.

The EKG trial ran from 30th October until 11th December 2014 (42 days) and Figure 49 shows the current draw over this period. The initial current draw was 140A which dropped to around 50A at the end of the active treatment. Figure 49 shows two peaks in the current on 23rd and the 26th November which may correspond to rainfall events which are likely to have increased the conductivity of the ground (Electrokinetic Ltd 2015b).

The EKG large cell tests indicated a power consumption of 32.6MJ/m3 of soil treated. (Electrokinetic Ltd 2015b). The measured median current demand per meter of electrode were as follows:

- Anodes: 0.51A / meter length of anode (Max. 1.75A, Min. 0.27A).
- Cathodes: 0.82A / meter length of cathode (Max. 1.24A, Min. 0.54A).

No inclinometers were installed in the embankment and there are no records of any slope monitoring.



Figure 48: Load displacement testing data for the tested anode soil nails (Electrokinetic Ltd 2015b)





Figure 49: Plot of current draw against time for the EKG treatment (after Electrokinetic Ltd 2015b)



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4 Effectiveness of Trials

The four EKG trials were varied in their purpose and implementation. The EKG trials on the M5 Junction 7 Off-slip, the A21 Stocks Green and the A419 Rat Trap embankments were effectively earthwork remediation schemes aimed at:

- remediating relatively shallow slips (1m to 2m deep);
- minimising disruption to the network; and
- reducing environmental impact.

Hence, their focus was on the implementation of a remedial works scheme on the active road network.

The A56 Woodcliffe EKG trial appears to have been undertaken with the following aims:

- investigation of the potential for the EKG treatment of a deep landslide slip surface (6m to 12m deep);
- to demonstrate installation of EKG on an active landslide site with difficult access; and
- to assess the use of EKG to remove/control groundwater on a landslide, the movement of which is controlled by groundwater.

All four of the sites had been subject to ground investigation to investigate the earthwork problems and, as such, there was a reasonable level of ground materials knowledge.

The groundwater and movement monitoring of the four sites was varied both in coverage and timing/duration (before, during, short-term post-EKG and long-term post-EKG treatment).

The A419 Rat Trap embankment slip observed (WSP 2102 and Electrokinetic Ltd 2015a) was not identified during the ground investigation. During the inspections of the site for this project various features were identified which bring into question the existence of a shallow slide (Section 2.4.3). Hence, the effectiveness of the EKG treatment cannot be determined with confidence for this site. It is important to note that the Geotechnical Risks at this site were not managed in accordance with HD22 and the works were carried out without full involvement of Highways England's Geotechnical Team.

As part of the scheme, the M5 Junction 7 embankment was regraded to a depth of up to 2.8m (Figure 34). As the EKG treatment was designed to treat the top 3.0m of ground, it is difficult to determine with certainty if the regrade works or the EKG trial had been most effective. The Geotechnical Risks at this site were not managed in accordance with HD22 and the works were carried out without full involvement of Highways England's Geotechnical Team. This caused problems with all aspects of the design and construction process.

Soil nail pull out tests for the four sites typically yielded capacities at or above the design values, indicating ground improvement and that the resulting soil/nail bond had been achieved.

The ground improvement aspects of the EKG treatment were only investigated in detail during the M5 and A21 trials. The M5 trial included post-EKG sampling and testing, but this was rather limited. We understand that further investigations were undertaken in 2014, but we have not seen these. The A21 trial did not have any post-EKG verification sampling and testing, hence, the only indications of the improvements were the results from the EKG Rosli and Large Cell tests during executed during the design of the trial. The A21 GFR by BBMM (2014) indicated that the slope has changed from a Class 1A (High Risk) earthwork to a Class 3A (Negligible Risk) earthwork.

The A21 Stocks Green trial was subject to groundwater and inclinometer monitoring before, during and after (short-term) the EKG trials. The groundwater monitoring was relatively infrequent but the installations were generally dry before and during the trial. It is not known if any ongoing monitoring is being undertaken. BBMM (2014) recommended improved monitoring of groundwater levels. During our site inspection in 2017, passive groundwater flow from cathodes was observed at some locations (Figure 7).

The M5 trial did not have any inclinometer installations and all bar one of the piezometers which were installed in the embankment were destroyed. Soil water potential meters were installed and used to monitor groundwater potential, and these showed some response to rainfall and EKG treatment. It is not known if any ongoing monitoring is being undertaken. The M5 trial provided good insight into the effectiveness of the electroosmosis with EKG active drainage yielding over 100 times that of passive drainage from the cathodes.

The A56 Woodcliffe trial was well instrumented with inclinometers and piezometers. The piezometers yielded high quality data before, during and after (short-term) the EKG trials. There appears to be no inclinometer data provided during or after the EKG trial. However, due to the limited extent of the trial, there may not have been an observable response in slope movement to the treatment. It appears that longer term post-EKG groundwater and inclinometer data was not collected as part of the EKG trial.

Due to the regrading works, it is difficult to determine if the M5 EKG trial has been successful in the widest sense, although it does appear that the combination of regrading and EKG treatment has successfully stabilised to slope. The improvements in the ground properties from very limited testing appear to suggest that the EKG has had a positive effect on stability, though there is no long-term detailed investigation, monitoring or assessment to verify this.

The A21 Stocks Green EKG trial appears to have been successful as the earthwork is now assessed as being a 'negligible risk' and the environmental habitat, in particular the Dormouse habitat, has been preserved (Figure 50). There is no post-EKG short- or long-term detailed investigation, monitoring or assessment to rigorously verify the effectiveness.

The A56 Woodcliffe EKG trial has provided a very good data set on the response of the piezometers to rainfall events and the EKG removal and control of groundwater in the slope. Unfortunately, the monitoring reported continued to only five weeks after the EKG trial and hence, no rigorous conclusions can be drawn regarding the longer term effectiveness of the EKG installation.

Of all the projects, the only financial cost data available is for the A21 Stocks Green site which apparently cost £662,882 at 2012 prices (BBMM 2014). This yields a treatment cost of



 $£2,900/m^2$ of embankment slope. (These costs equate to around £790,000 for the scheme and £3,400/m² at 2017 prices.) Given the very limited information, no assessment of the cost effectiveness of the EKG could be made.



Figure 50: Stocks Green 1 site 12 months after EKG trial (BBMM 2014)



5 Lessons Learnt

From the three trials, a number of general lessons can be learnt with regard to the design, implementation and verification of trials of any remedial works and the specific issues encountered with the EKG technique.

5.1 General

As discussed in Section 4, the A21 Stocks Green, the M5 Junction 7 and the A419 Rat Trap trials appear to have been conducted as earthworks remediation schemes by the maintaining agent and probably utilising maintenance/repair budgets. Hence, the monitoring and post-trial verification studies vary in extent and timing/duration and appear to be lacking the methodical and rigorous approach required for definitive trials of the EKG technique.

The A56 Woodcliffe EKG trial was undertaken as a small-scale demonstration trial, particularly aimed at assessing the effectiveness of EKG for active dewatering. As such the monitoring of groundwater levels prior to, during and immediately following (five weeks) was of high quality. However, as the groundwater monitoring presented in the GFR (Electrokinetic Ltd 2013) only contained data for the five week period immediately following the trial. The opportunity to present the long-term effectiveness of the techniques was missed.

From this review of the trials, it is clear that making use of real network schemes to trial innovative techniques is beneficial. However, the trials must be set up to adequately investigate and monitor the repair at that time and also in the longer term. All Geotechnical works must be managed in accordance with HD 22 and HD 41, and all geotechnical trials must be fully managed by Highways England's Geotechnical Team. To achieve this, it is recommended that:

- A trial project team is set up with a specific task of designing, implementing and monitoring the trail.
- This team is not limited or encumbered by the day to day management of the highway. It is also important to ensure that the trial does not impose any undue risks to the continued operation and maintenance of the network (and the environment associated with it) and that any such risks are identified, are at a level that is acceptable, and a plan to eliminate, manage or mitigate those risks is in place.
- An adequate budget is set aside for designing, implementing and monitoring the trail.
- Monitoring should continue for a number of years following the implementation of the trial.
- Specific reporting on the trial should be undertaken. Relying on the content and structure of Geotechnical Feedback Reports to provide appropriate information to evaluate and compare trials of innovative geotechnical repair techniques may hinder the process.

5.2 Specifics

5.2.1 EKG System and Components

From the four EKG trials, a number of issues were highlighted with the system components which need to be addressed to ensure that trials proceed in a timely and cost effective manner, whilst providing high quality data for the assessment of the technical and cost effectiveness of the technique. These include:

- More robust anode/cathode couplers to prevent failure of couplings as experienced on the A21 Stocks Green project.
- More effective method(s) for the collection and flow monitoring of the water discharge from the cathodes, possibly a development of the system used on the A56 trial.
- Provision of corrosion protection for the anode soil nail head assemblies which were observed to have corroded during the site inspections for this project.

There are no specific comments in the reports on the health and safety aspects of the electrical installations. There is comment in BBMM (2014) and Amey (2014) regarding having to switch off the EKG trial during emptying of the plastic bags used for water discharge measurement from the cathodes.

Currently there is only one supplier of the EKG system and this is likely to provide procurement issues with the adoption of the system.

The fact that Electrokinetic Ltd do not undertake the design of the electrical installation or the overall design of geotechnical remediation schemes raises significant issues of design responsibility and certification.

There is very limited information on the cost of the EKG treatment from which to make a commercial assessment of the cost benefit of the technique. This will need to be addressed to aid consideration of the technique as a viable option and hence future uptake of the technique.

5.2.2 Design of EKG Trials

The investigations and testing of soils as part of the design of the EKG installation is very specific to the technique and appears to be well developed. However, during the review of the trials a number of issues were identified which should be addressed before any further application of the technique, these include:

- The testing of soils for properties, behaviours and parameters specific to the EKG process would be easier if the Large Cell test 'casing' was pushed into soils on site to obtain samples, thus enabling more Large Cell tests to be undertaken to determine likely electrical current draw.
- An early assessment of the likely current draw would help to determine the appropriate electrical supply requirements.



- Splitting the EKG installation up into discrete panels would enable any changes in the electrical conductivity of the ground to be accommodated by varying the current supply to the discrete area; this would help to reduce power usage.
- The addition of a shunt resistor into each of the electrical control circuits so that the current flows can be monitored and data logged. This would enable accurate determination of the power consumption.
- The water discharged from the cathodes has high pH values (Amey 2014) and could present a hazard to personnel, equipment and the environment. The assessment, control and disposal of the water needs to be factored into the design of trials.

5.2.3 Verification and Monitoring

The most significant issues with all the EKG trials were the lack of post-EKG trial verification testing of soil parameters and lack of adequate pre-, during and post-trial monitoring. Specific recommendations include:

- Installation of inclinometers to allow appropriate monitoring pre-, during and post-EKG trial (short- and long-term) should be undertaken.
- Installation of data logged/telemetry piezometers and rain gauges to allow appropriate monitoring pre-, during and post-trial (short- and long-term).
- Installation of additional sacrificial EKG soil nails and conventional control soil nails for post-EKG treatment testing and exhumation to determine adhesion/interface shear and also the extent of zone of influence should be undertaken.
- Post-EKG treatment ground investigation including in situ testing, laboratory testing and chemical/mineralogical testing should be planned to enable post-EKG treatment verification in both the short- and long- term. The mineralogical testing would assist with determining the contribution of cementation, ion exchange and flocculation to the increases in shear strength.

5.2.4 Life Cycle Assessment

A cradle-to-site Life Cycle Assessment (LCA) has been conducted for the three techniques – willow poles, FRS and electroosmosis – and a crushed granular fill control technique. The results of the LCA are reported in detail by Leal et al. (2018) and included consideration of two failure depths of 1.0m and 2.5m (the 1.0m failure depth was not considered for electroosmosis) and various transport distance options. It was found that at both failure depths, and for all transport cases, the greatest environmental impact was for the Granular Rock Fill Replacement control. At 1m and 2.5m failure depths this technique resulted in an impact of 51 to 80 kgCO2e/m² and between 109 and 174 kgCO2e/m² of failed slope respectively, depending upon the transport distance assumed.

Willow Poles had the least impact, resulting in 4 to 8 kgCO2e/m2 to 8 to 12 kgCO2e/m² of failed slope respectively. For the 2.5m failure depth, electroosmosis was the second best performing technique, with an average impact of 14 kgCO2e/m². FRS had an impact ranging between 16 and 35 kgCO2e/m². For techniques requiring large quantities of materials and



movements of these materials across substantial distances (e.g. Granular Rock Fill Replacement and Willow Poles), it was found that transportation accounts for more than half of the total impact.



6 Summary and Conclusions

Three of the four EKG trials (A21 Stocks Green, M5 Junction 7 and A419 Rat Trap) were undertaken as practical remedial works for known relatively shallow (1m to 2m deep) earthwork embankment instability issues. The fourth EKG trial (A56 Woodcliffe) was undertaken to demonstrate, on a small scale, the effectiveness of EKG for primarily active dewatering of fine grained soils, but also ground improvement.

Based on the GFRs and the inspections undertaken by the authors for this project, the A21 and M5 trials appear to have been successful in stabilising the shallow landslides whilst reducing disruption to the network and damage to ecologically sensitive sites. However, the ground improvements by EKG treatment cannot be rigorously assessed due to limitations in the extent and duration of post-EKG treatment ground characterisation, groundwater monitoring and movement monitoring.

The results of the A419 Rat Trap are of uncertain value as the interpretation of the existence of a shallow slide seems to be questionable. However, the trial provides additional information on the installation and operation of the EKG system.

The A56 trial provides a high quality data set to demonstrate the effectiveness of the active dewatering of a deep (6m to 12m) landslide using the EKG technique. However, the detailed rigorous assessment was compromised by the limitations in the extent and duration of post-EKG treatment ground characterisation, groundwater monitoring and movement monitoring. EKG active dewatering effect on ground water levels was significant and appears effective in the fine grained soils. This technique has the potential to be a valuable means of groundwater removal and control in fine grained soils with high water tables, a situation which is often problematic for permanent works, and particularly for the temporary works required to install permanent works.

The cost of EKG treatment needs to be determined to enable assessment of the commercial viability of the EKG treatment in a number of different situations.

Lessons learnt from the trials and this review are detailed in Section 5. The following general issues should be addressed in any future EKG or other trials of innovative techniques:

- the purpose and limitation of the trial should be clearly set out; and
- appropriate planning and budget for ground investigation, sampling, testing and monitoring before and after, both short-term (weeks) and long-term (years), the trial to enable verification of the effectiveness.

Specific issues related to the EKG trials include:

- that there is currently there is only one supplier of the EKG system,
- the need for more robust and effective system components and monitoring systems (electrical and water discharge),
- the need for early assessment of likely current draw coupled with discrete EKG panels with monitored and controlled current supply, and



• the need for post-trial ground investigation, in situ testing, laboratory testing and monitoring to determine effectiveness and the longevity, and thus the design life, of the EKG processes.

Based on the current information it is recommended that post-EKG trial ground investigation, in-situ testing, laboratory testing and monitoring are undertaken for the A21 Stocks Green site and the A56 Woodcliffe site. Any continued work should follow the principles highlighted in Section 5.

To assist with advancing the potential application of EKG treatment it is recommended that further trial sites are selected and that the trials are undertaken using the principals outlined in Section 5.

In conclusion it is considered that EKG treatment can be a successful dewatering and ground improvement technique for shallow slope failures in fine grained soils. It has the benefit of requiring relatively small plant and hence relatively low disruption to both the highway network and the environment. The A21 Stocks Green trial clearly demonstrates the application of the technique in and adjacent to existing vegetation to minimise disruption to protected habitats (Dormice in this case).

The application of EKG for the active dewatering of deeper landslides is of significant interest. It has the potential to remove / control groundwater on larger and deeper active slips for which remedial works may be challenging to install. In such situations, the EKG treatment could enable temporary works to be undertaken with more favourable ground water conditions. This is often a particularly difficult and risky operation.


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Appendix APreliminary Guidance for Trials of ElectrokineticGeosynthetic Slope Stabilisation



Preliminary Guidance for Trials of Electrokinetic Geosynthetic Slope Stabilisation

Revision 0 Date (October 2018) Document Owner: Jan Marsden Document Author: Ian Nettleton



Content

- 1. Site Selection
- 2. Site Characterisation and Monitoring
- 3. Design for EKG Slope Stabilistaion
- 4. Normative References
- 5. Informative References



Version	Date	Details of amendments
Rev. 0	10 2018	This document has been written to provide preliminary guidance for future trials of Electrokinetc Geosynthetic treatment of Slopes. While written broadly in the style of the Future DMRB, compliance with the associated drafting rules in neither intended nor implied. This document is not intended to form part of the DMRB in the immediate future.
Rev. 1		

Release notes



Foreword

Publishing information

This document is published by Highways England.

Contractual and legal considerations

This is a Highways England document that is intended to be used by the Geotechnical Team and Project Sponsors, and their designers and constructors to specify the installation of live willow poles for stabilising highway slopes. It is written, as far as possible, in the MDD style but does not form part of the DMRB.

Introduction

Background

Shallow slope failure is a widespread and costly maintenance problem that affects highway earthworks, particularly slopes in over-consolidated clays. In most cases the failures occur at depths which are shallower than 1.5m (Ref. 1.I).

Installation of live willow poles offers an easy, relatively rapid and cost effective method of ensuring that vegetation is successfully established both at surface level and at depth within a slope. The live willow poles provide a form of vegetated soil nailing or dowelling which provides immediate improved slope stability and can be used in the prevention, and repair, of shallow slips on highway embankment and cutting slopes. Benefit to the stability of the slope is also gained subsequently over time through establishment of a root system and a reduction in the soil moisture.

A specification for the installation of live willow poles is presented in the main body of this document and a design approach, building on experience gained on a number of trials, is detailed in the Appendix.

Assumptions made in the preparation of the document

The assumptions made in GG 100 *Introduction to the Design Manual for Roads and Bridges* apply to this document.



Acronyms and symbols

Acronym	Definition
Term 2	Definition [Use the tab key for new row]

Symbol	Definition
Term 2	Definition [Use the tab key for new row]

Terms and definitions

Term	Definition
Term 1	Definition [Use the tab key for new row]



1. Site Selection

1.1. DMRB principles, especially those set-out in HD22 (Ref. 1.N), shall be followed.

Slope Failure Characteristics

- 1.2. The location, depth, characteristics and extent of any failures of the slope and any water bearing strata shall be established.
- 1.3. The movement of the slope shall have been monitored and the depth of the failure surface(s) shall be determined.
- 1.4. Critical groundwater levels within the slope shall have been determined.
- 1.5. The nature and cause of the slope failure shall be fully investigated and documented.
- 1.6. A targeted and clearly defined slope stabilisation strategy shall be defined.

Suitability of Soils for Electrokinetic Geosynthetic (EKG) Slope Stabilisation

- 1.7. Soils suitable for EKG slope stabilisation shall be used where the treatment of fine grained soils is required to improve the slope stability.
- 1.7.1. A measure of the likely performance of the EKG technique can be gained by measuring the Electrical Conductivity, in accordance with BS 1377:1990 Part 3 (Ref. 2.N), of the soil to be treated. Cassagrande (Ref. 1.I) and Mitchell (Ref. 2.I) indicate that a treatable range is between 5 mSm⁻¹ and 50mSm⁻¹.
- 1.8. For effective application of electroosmosis the hydraulic flow of water through the soil shall be less than the electoosmotic flow.
- 1.8.1. The electroosmotic flow of water through a soil should be expressed using the Helmholtz Smoluchowski model (Ref. 3.I) as follows:

$$Q_e = k_e i_e A$$

Where:

 Q_e = electroosmotic flow rate (m³s⁻¹)

 K_e = coefficient electroosmotic permeability (m²sV⁻¹)

 I_e = electrical potential gradient (Vm⁻¹)

A = area across which flow is taking place.



2. Site Characterisation and Monitoring

Slope Characterisation

- 2.1. The following general characteristics of a potential site shall be recorded:
 - 1. slope details: natural or formed, cutting or embankment;
 - 2. crest elevation;
 - 3. slope inclination;
 - 4. orientation of slope fall line;
 - 5. geometry: vertical height, width, and slope length;
 - 6. depth and extent of the failure(s);
 - 7. location and extent of previous significant repairs;
 - 8. evidence of any water bearing strata or drainage defect;
 - 9. existing vegetation cover at the site.

General Soil Characterisation

- 2.2. The soils at the site shall be characterised as follows:
 - 1. soil type, colour, structure, and weathering;
 - 2. particle size distribution;
 - 3. plastic and liquid limits;
 - 4. in-situ moisture profiles;
 - 5. in-situ shear strength (drained and undrained) e.g. cone penetration penetrometer test (CPT) or standard penetration test (SPT)
 - 6. triaxial laboratory shear strengths testing (drained and undrained);

Monitoring

- 2.3. If not already installed at the site, the following monitoring instrumentation shall be installed:
 - inclinometers to determine the depth of the slip surface(s) and rates of movement;
 - 2. data logged rain gauge to record rainfall events;
 - 3. data logged piezometers for groundwater monitoring;



Electrokinetic Soil Characterisation

2.4. The soils at the site shall be characterised as follows:

Test	Methodology	Purpose
Electrical conductivity E _c	BS 1377-3:2018 (Ref. 1.N	Evaluate likely performance of EKG technique.
Coefficient of electroosmotic permeability k _e	Rosli Cell (modified triaxial cell) (Ref. 4.I)	Determine treatment times; degree of negative pore water pressure achievable; degree of electroosmotic
Electroosmotic consolidation EO		consolidation achievable at various voltage gradients; and the time and electrical energy required to reach 90% consolidation.
Large Cell tests	Electrokinetic Ltd Shear Box (Ref. 5.I)	General bulk soil parameters; anode proximal soil parameters and soil nail / soil bond strength.



3. Design for EKG Slope Stabilisation

- 3.1. Based on the findings of the Site Characterisation and Monitoring (Clause 2) a parametric assessment of the slope stability shall be undertaken to determine the sensitivity of the slope to potential effects of the EKG treatment including:
 - Electroosmotic (EO) ground improvement: changes the bulk soil parameters – due to consolidation, cementation, precipitation, reduction in plasticity, and increases in cohesion;
 - 2. **Drainage:** reduction in ground water levels and pore water pressures due to active EKG drainage during treatment and long term passive drainage;
 - Reinforcement: enhanced soil nail / soil bond strength due to cementing; and
 - 4. **Modification:** physio-chemical modification of the soil largely by cation exchange.
- 3.2. Following the parametric study, the specific targets for EKG treatment and the target improvements shall be identified and recorded to enable verification of the success of the trail.
- 3.3. A suitable EKG installation shall be designed to achieve the targets identified in Clause 3.2. The outcome of the design shall include:
 - 1. electrode array spacing, length, inclination and type of electrodes;
 - 2. electrical system voltage gradient, active treatment duration, direct current power supply, current draw during active treatment.
 - 3. Assessment of the cost of the treatment and the carbon footprint.
- 3.4. The design of the soil nail element shall be in accordance with BS 8006-2: 2011 (Ref. 3.N).
- 3.5. Control areas of the slope shall be selected monitored as per the EKG treated areas. The control areas shall include additional soil nails of the same form as the EKG anode electrode, but which will not be subject to EKG treatment.



3.6.	Typical EKG installation and characteristics would be:
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Electrokinetic Geosynthetic Installation Parameter*	Typical Range
Anode Horizontal Spacing (m)	1.0 to 3.0
Anode Downslope Spacing (m)	1.0 to 2.8
Anode Inclination (°)	10 to 20
Cathode Horizontal Spacing (m)	1.0 to 3.0
Cathode Downslope Spacing (m)	1.0 to 5.8
Cathode Inclination (°)	-3 (below horizontal)
Voltage (V)	40 to 95*
Current Draw (A)	12 to 716 (generally 50 to 400** for main trials)
Energy Consumption (MJ/m ³)	22.1 to 32.6

* Based on data from four projects.

** Per treatment panel.

EKG Slope Stabilisation Installation and Operation

- 3.7. Minimal vegetation removal shall be undertaken to enable access for the electrode installation drill rigs. This is likely to be limited to brush and shrub clearance and the removal of only isolated trees and branches.
- 3.8. During the EKG treatment the voltage and current for the EKG treatment shall be data logged to monitor the performance against the laboratory Electrokinetc Characterisation (Clause 2.4).
- 3.9. During the EKG treatment the slope piezometers, rain gauge and the discharge from the cathodes shall be monitored, ideally using data loggers and/or remote telemetry.

Post-EKG Slope Stabilisation Verification and Monitoring

- 3.10. Upon completion of the EKG treatment a detailed ground investigation and monitoring regime shall be undertaken to enable verification of the effectiveness of the EKG trial.
- 3.10.1. It is recommended that immediately post EKG treatment that a ground investigation should be undertaken to determine:
 - 1. soil type, colour, structure, and weathering;
 - 2. particle size distribution;
 - 3. plastic and liquid limits;
 - 4. in-situ moisture profiles;
 - 5. in-situ shear strength (drained and undrained) e.g. cone penetration penetrometer test (CPT) or standard penetration test (SPT)



- 6. triaxial laboratory shear strengths testing (drained and undrained);
- 3.11. Soil nail testing to determine the soil nail / soil bond strength shall be undertaken on EKG soil nails and the control nails.
- 3.12. Monitoring of the inclinometers, piezometers and the slope condition shall be undertaken for a minimum period of two years after the completion of construction to provide verification of the effectiveness of the trial. At the end of the two-year period the trial shall be assessed and any further extension to the monitoring determined.



4. Normative References

	Title
Ref. 1.N	DMRB Document HD 22, Managing geotechnical risk.
Ref. 2.N	BSI. 2018. Methods of test for soils for civil engineering purposes. Chemical and electro-chemical testing. BS 1377-3:2018. BSI, London, UK.
Ref. 3.N	BSI. 2011. Code of Practice for strengthened/reinforced soil and other fills: BS 8006-Part 2, soil nails. BSI, London, UK.



5. Informative References

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Ref.	Mitchell, J K. (1993). Fundamentals of Soil Behaviour. 2nd Ed. John Wiley & Sons
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Innovative Geotechnical Repair Techniques



Work to evaluate the effectiveness of innovative geotechnical repair techniques for slopes has been commissioned by Highways England. The techniques are the planting of live willow poles, fibre reinforced soil and electrokinetic geosynthetics. These techniques were used in place of conventional approaches to repair in order to reduce the overall impact of various challenges including environmental constraints (habitat and visual), access and utility constraints, and to address the need to reduce the scale and/or cost of traffic management and traffic delays. Trials of the techniques have been undertaken over the preceding 20 years or so but monitoring was generally limited to just a few years post-construction. Longer term evaluation has not generally been undertaken. This report presents an assessment of the effectiveness of electrokinetic geosynthetics as an aid to increased stability and is one of a series for this project.

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