ELECTROKINETIC treatment of soils to:
aid dewatering
accelerate consolidation
enhance soil strength
control pore water pressure

Theory and recent practice

Colin Jones – David Alder

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Email **Colin Jones**: c.j.f.p.jones@ncl.ac.uk

Email **David Alder**: david.alder@electrokinetic.co.uk

Website: www.electrokinetic.co.uk

Structure of lecture

Background

Electrokinetic phenomena

Historic use of EK

Development of new delivery/ control systems

Research – practice

Application areas

Dewatering and consolidation

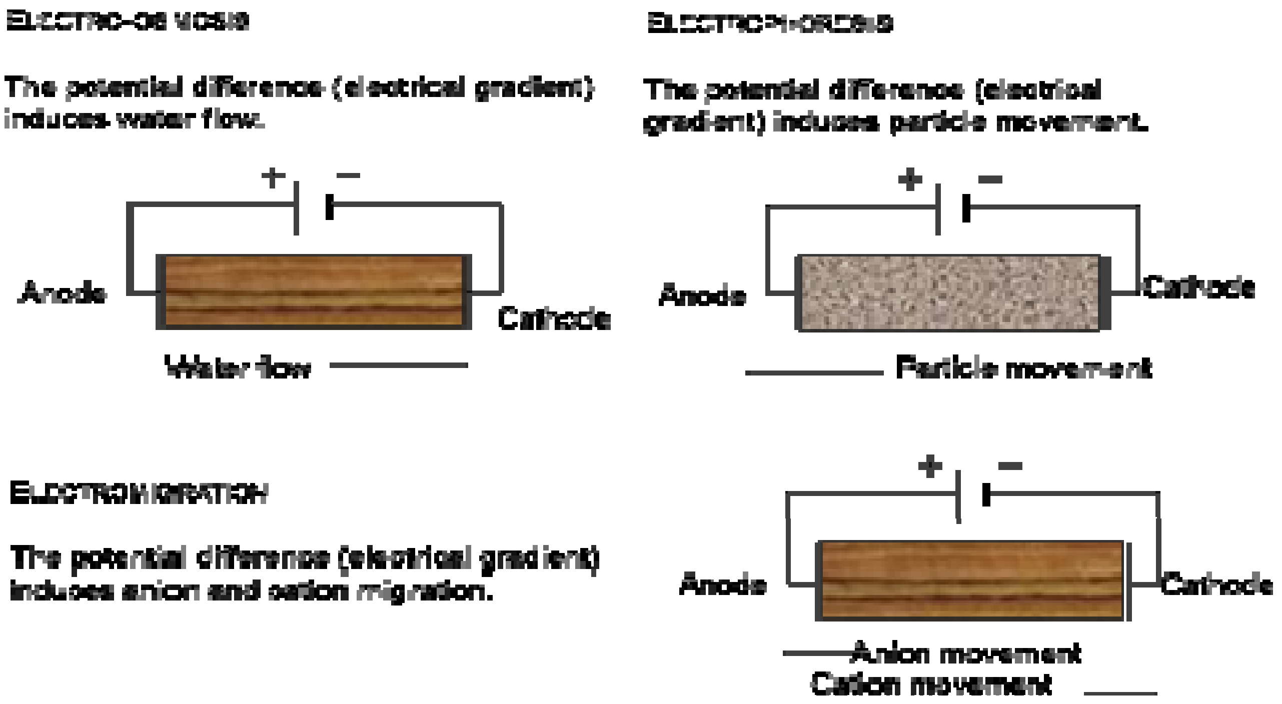
In-situ increase in shear strength

Control of pore water pressure

Electro-chemical treatment

Reference

Electrokinetic phenomena



ELECTRO-OSMOSIS

The potential difference (electrical gradient) induces water flow.

ELECTROPHORESIS

The potential difference (electrical gradient) induces particle movement.

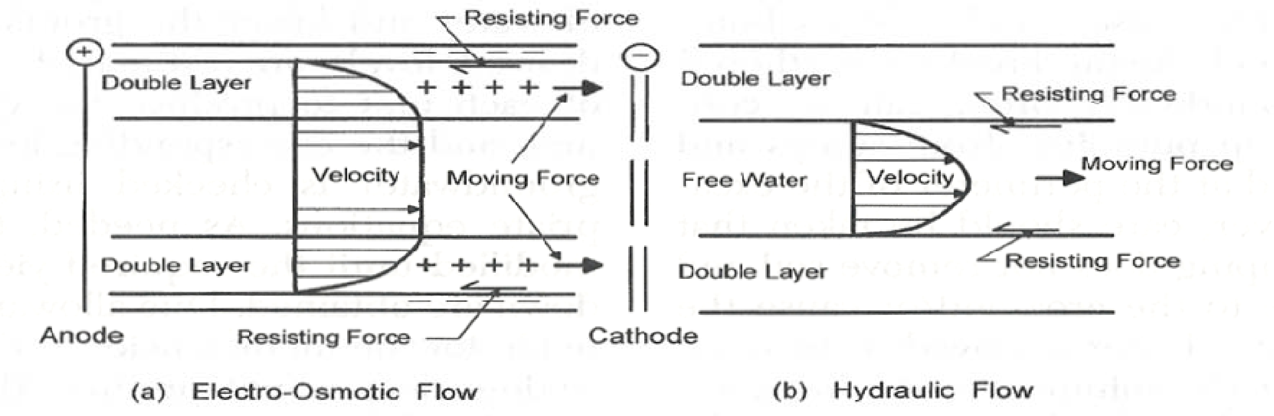
ELECTROMIGRATION

The potential difference (electrical gradient) induces anion and cation migration.

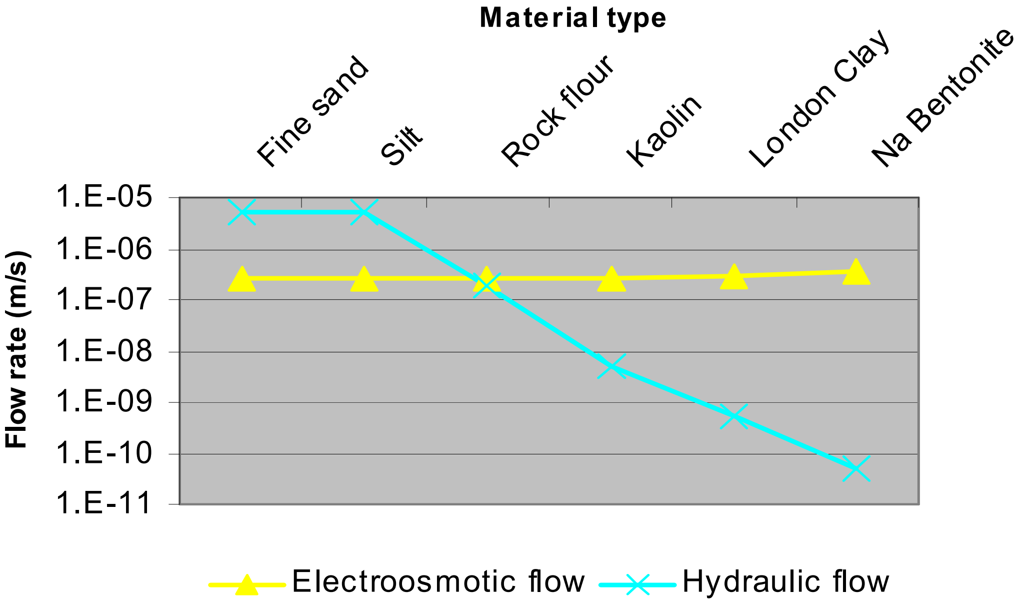
Water removed by electroosmosis is both interstitial and vicinal.

- Interstitial water is controlled by capillary forces.
- Vicinal water relates to molecules layered on the clay particles

Electroosmotic v hydraulic flow



(a) Electro-Osmotic Flow (b) Hydraulic Flow



$K_e : k_h \sim 1 \times 10^4$

Some historic uses of electroosmosis

Casagrande, 1939 – Stabilization of railway cutting and permitted safe construction

Casagrande, 1940 – Stabilisation of excavation for U-Boat pens

US Army Corps of Engineers, 1997 – Lowering of Piezometric level in clay core of East Branch Dam, Ohio

Casagrande 1967 – Ontario, Slope stabilisation using EO to generate pore water tension

Bjerrum, 1967 – Norway, EO consolidation used to stabilise quick-clay

Wade, 1975 – Stabilisation of 30m high slope in clayey silt

Casagrande, 1978 – Canadian Pacific Railway cuttings, EO used to strengthen slopes in weak soil and reduce land-take

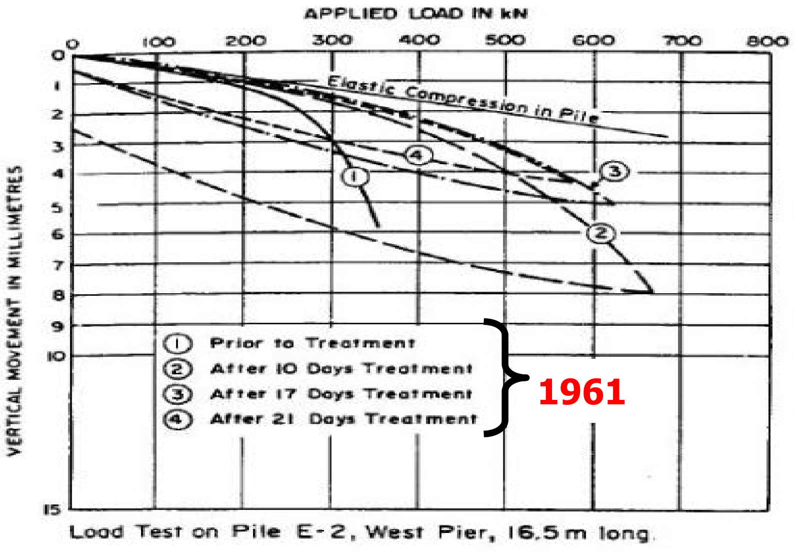
Milligan, 1959 & 1994 – Little Pic river, Pile load testing of steel pile EO treatment to improve skin friction

Casagrande (1939) - treatment of rail cutting

Clay/silt cutting
Work stopped due to instability

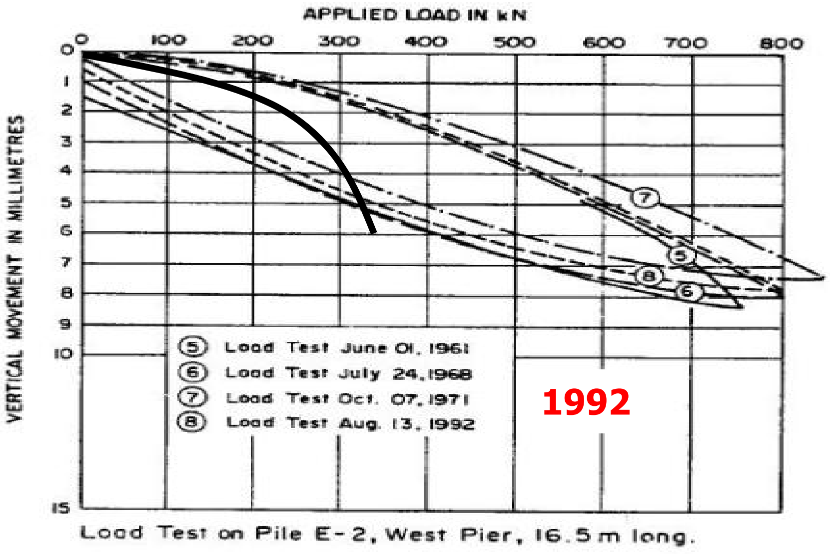
EO Treatment
7m deep steel electrodes @ 9m and 180V
Work recommenced after 2 days,
1.3 kWhr/m3 of excavation

Pic River bridge piles – Milligan (1994)



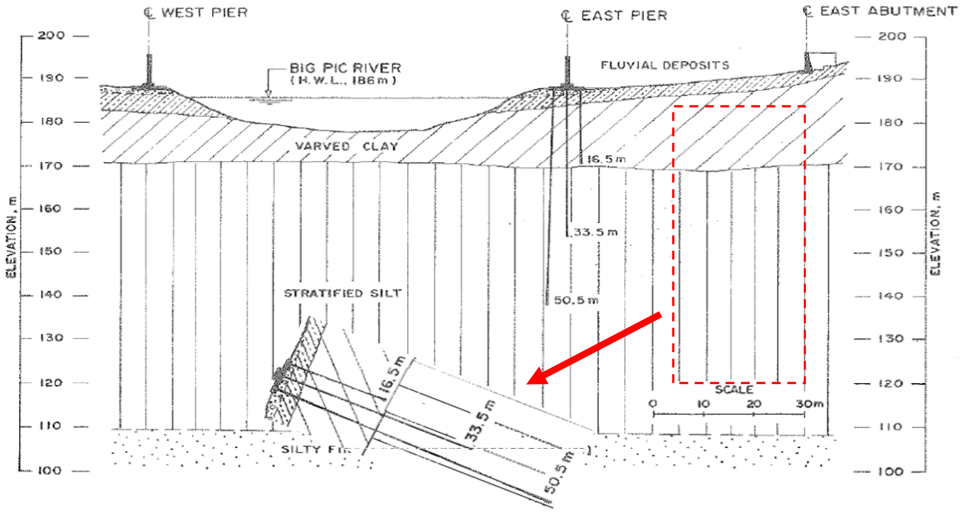
1961

Load Test on Pile E-2, West Pier, 16.5 m long.



1992

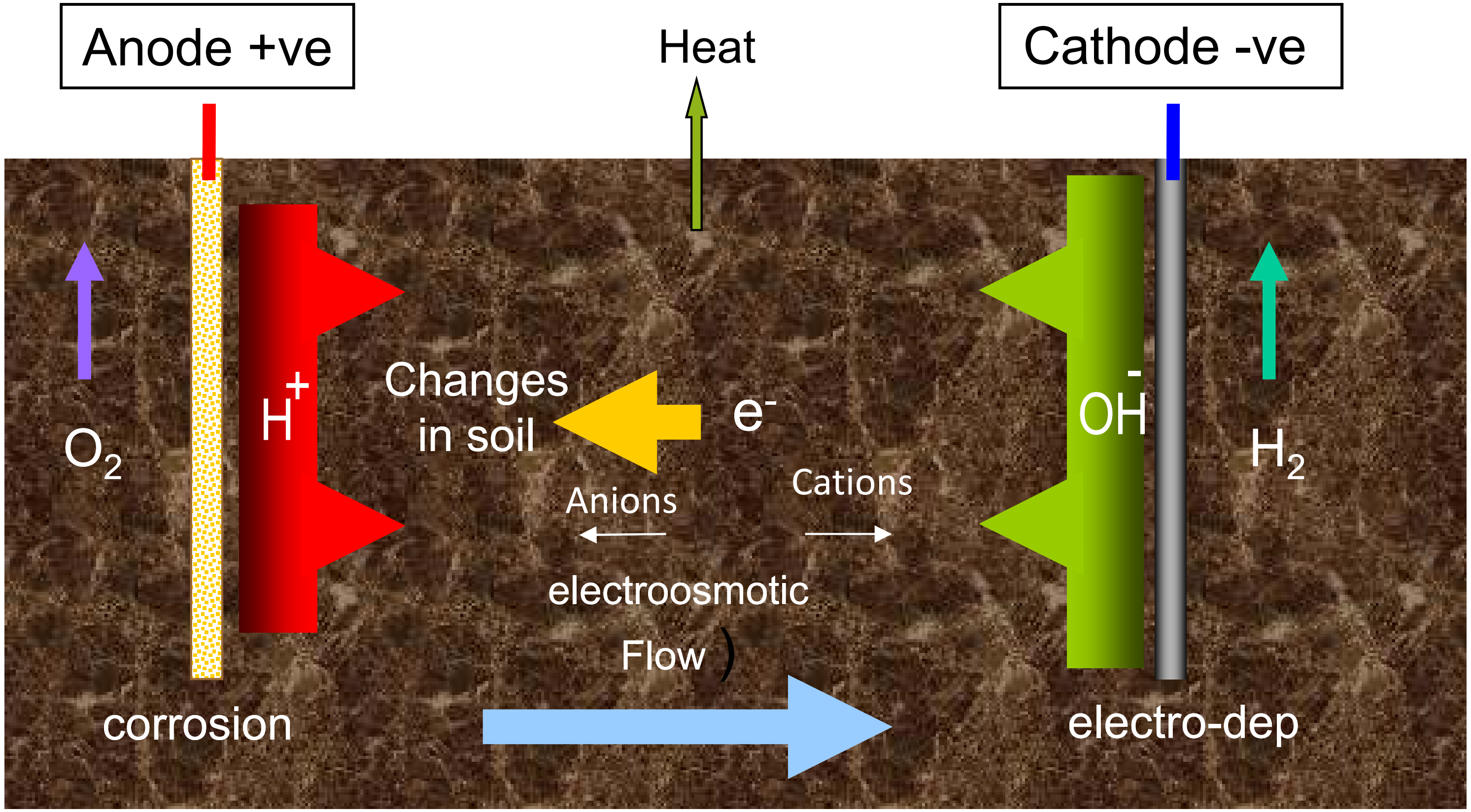
Load Test on Pile E-2, West Pier, 16.5 m long.



Conclusion

EO is effective, fast and permanent

Issues/effects needing consideration



Also: desiccation = poor electrical connection, high and low pH

Review of past EK projects show treatment dependent on:

1. Correct choice of materials to treat
2. Design of multi-functional electrodes
3. Control of treatment and boundary conditions

Necessary characteristics for electrodes

Conduct water in / out of the system

Transport gasses out of the system

Maintain good electrical conductivity

(Resist corrosion)

Electrode design must permit the treatment to be:

- Effective
- Efficient
- Reliable
- Economic

Combine electrokinetic phenomena with geosynthetic functions (EKG)

Electrokinetic phenomena

- Electroosmosis
- Electrophoresis
- Ion migration
- Electrolysis of water
- Heating
- Oxidation reactions
- Reducing reactions

Geosynthetic functions

- Drainage
- Reinforcement
- Filtration
- Separation
- Containment
- Membrane action
- Sorption

EKG electrodes provide

Engineered corrosion management (electrodes fit for purpose)

Dense network of electrical contacts (maintain conductivity)

Efficient drainage capacity to:

- Introduce / remove water
- Remove gasses

Exploitation of the traditional functions of geosynthetics
e.g. filtration, reinforcement, separation, containment

Formation in a variety of 2D and 3D shapes to suit individual applications

Combing electrokinetic phenomena with geosynthetic functions

Creates active geosynthetics

Electrokinetics + filtration + drainage = (EKDrain)
(e.g. Casagrande 1939)

- EK causes water to flow to the drain
- Drain provides filtration and drainage

Electrokinetics + reinforcement = (EKReinforcement)

(e.g. Milligan 1994)

- EK increases strength of soil and reinforcement / soil bond
- Reinforcement acts as normal

Control of boundary conditions

Drainage conditions

- open / closed anode
- open / closed cathode

Electrical contact (electrode design)

Electrode composition (electrode design)

Voltage gradient (applied voltage & electrode arrays)

Voltage control (switching)

Drainage configurations

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<tr><th>Drainage Regime</th><th>Boundary Conditions</th><th>Pore Water Pressure Distribution</th></tr>
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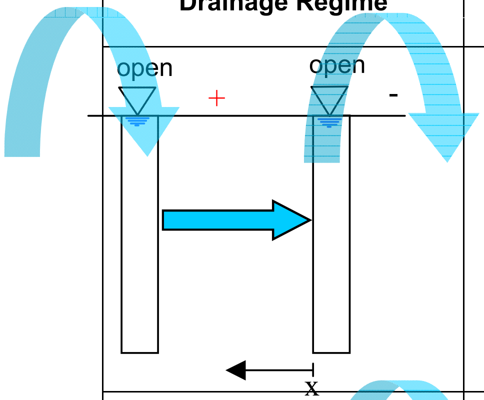
<td>
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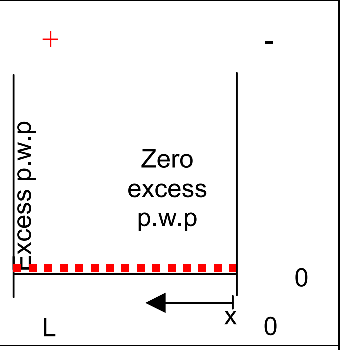
<td>Cathode:
$x = 0, V = 0, u = 0$
Anode:
$x = L, V = V_{max}, u = 0$</td>
<td>
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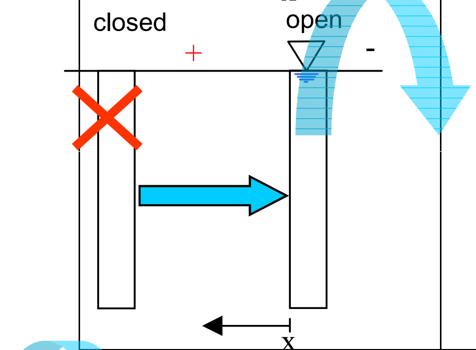
<td>
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$x = 0, V = 0, u = 0$
Anode:
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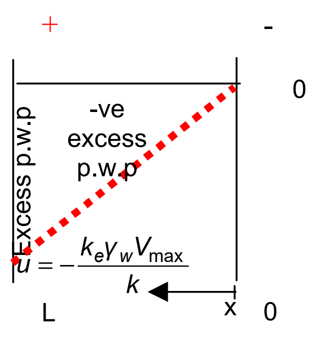
<td>
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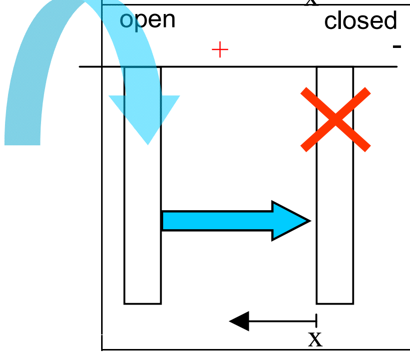
<td>
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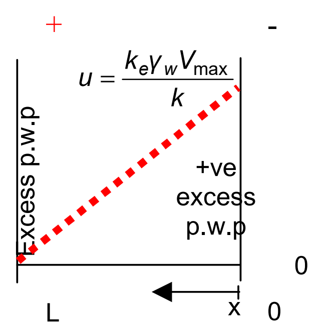
<td>
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Clean up & electrochemical treatment

Volume control, dewatering & strengthening

Volume control (expansion)

EKG Electrode design

Mk1

Mk4

Mk6

EKG Electrodes (planar)

Current electrodes for strengthening and consolidation

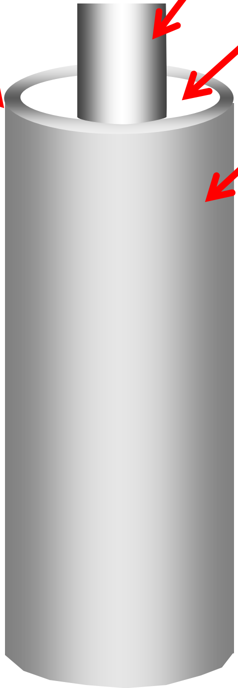
Anodes

Cathodes

Stainless steel mesh

filter

porous polymer drain



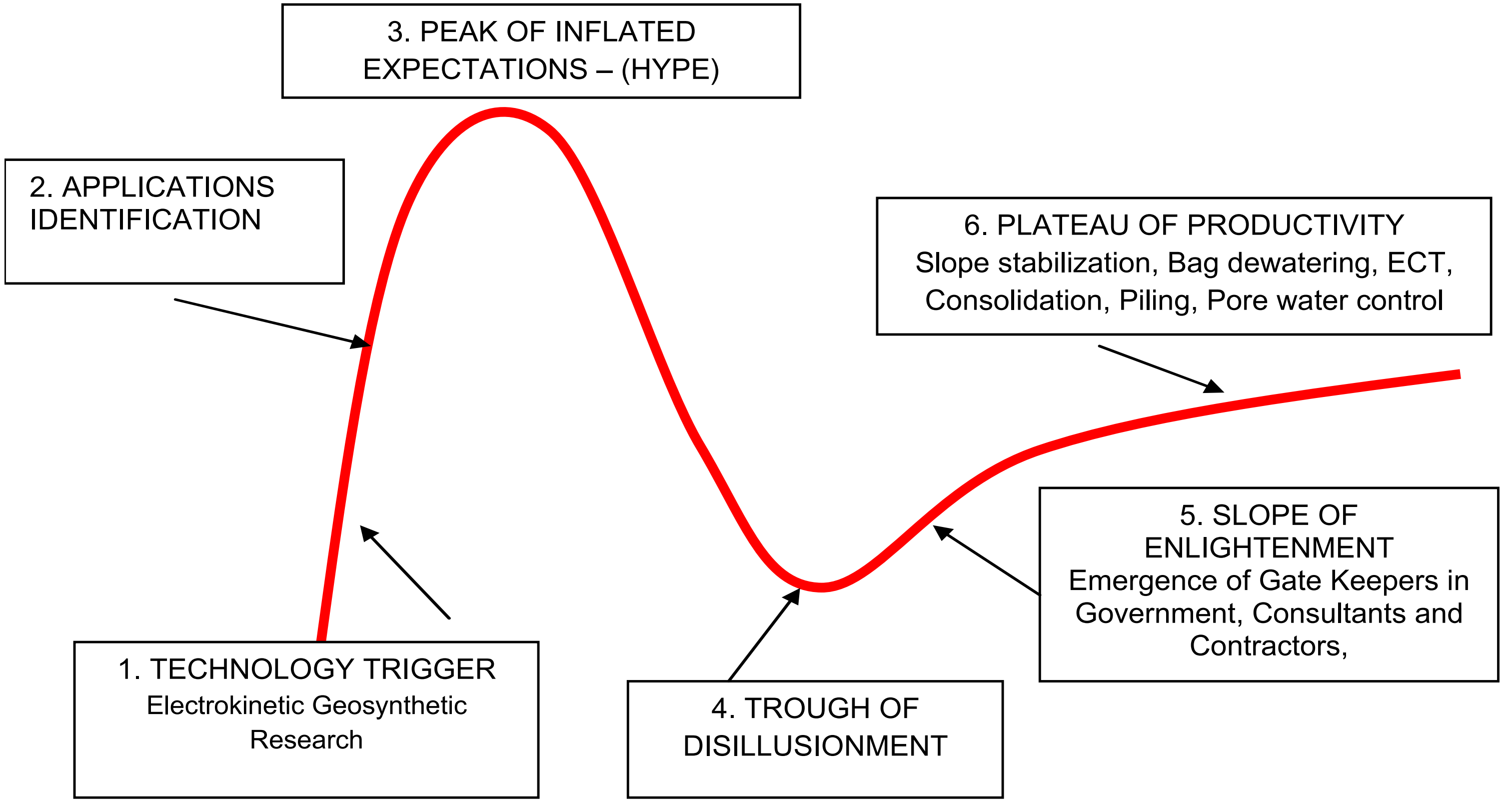
Tendon

Grout filled annulus

Anode tube

Development of the EKG concept

Research to practice - Gartner hype cycle



3. PEAK OF INFLATED EXPECTATIONS – (HYPE)

2. APPLICATIONS IDENTIFICATION

6. PLATEAU OF PRODUCTIVITY
Slope stabilization, Bag dewatering, ECT, Consolidation, Piling, Pore water control

5. SLOPE OF ENLIGHTENMENT
Emergence of Gate Keepers in Government, Consultants and Contractors,

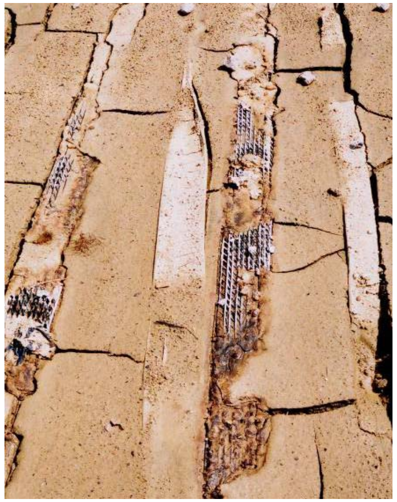
1. TECHNOLOGY TRIGGER
Electrokinetic Geosynthetic Research

4. TROUGH OF DISILLUSIONMENT

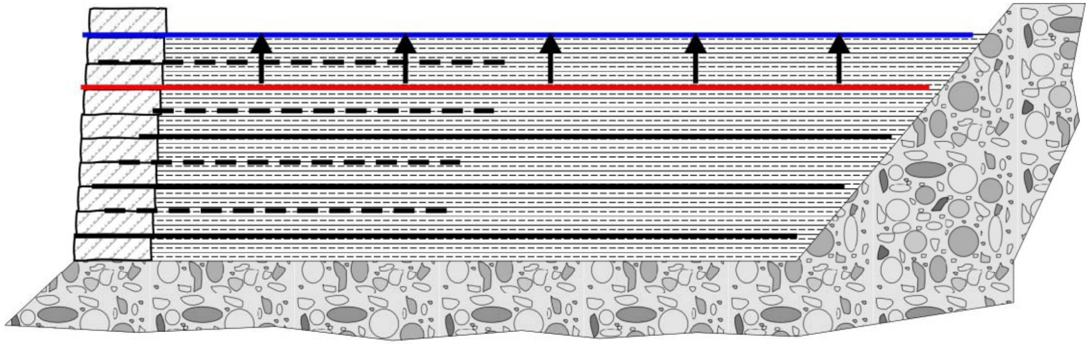
Research - 5m high reinforced soil wall constructed with liquid fill

Mixing Fill

Placement

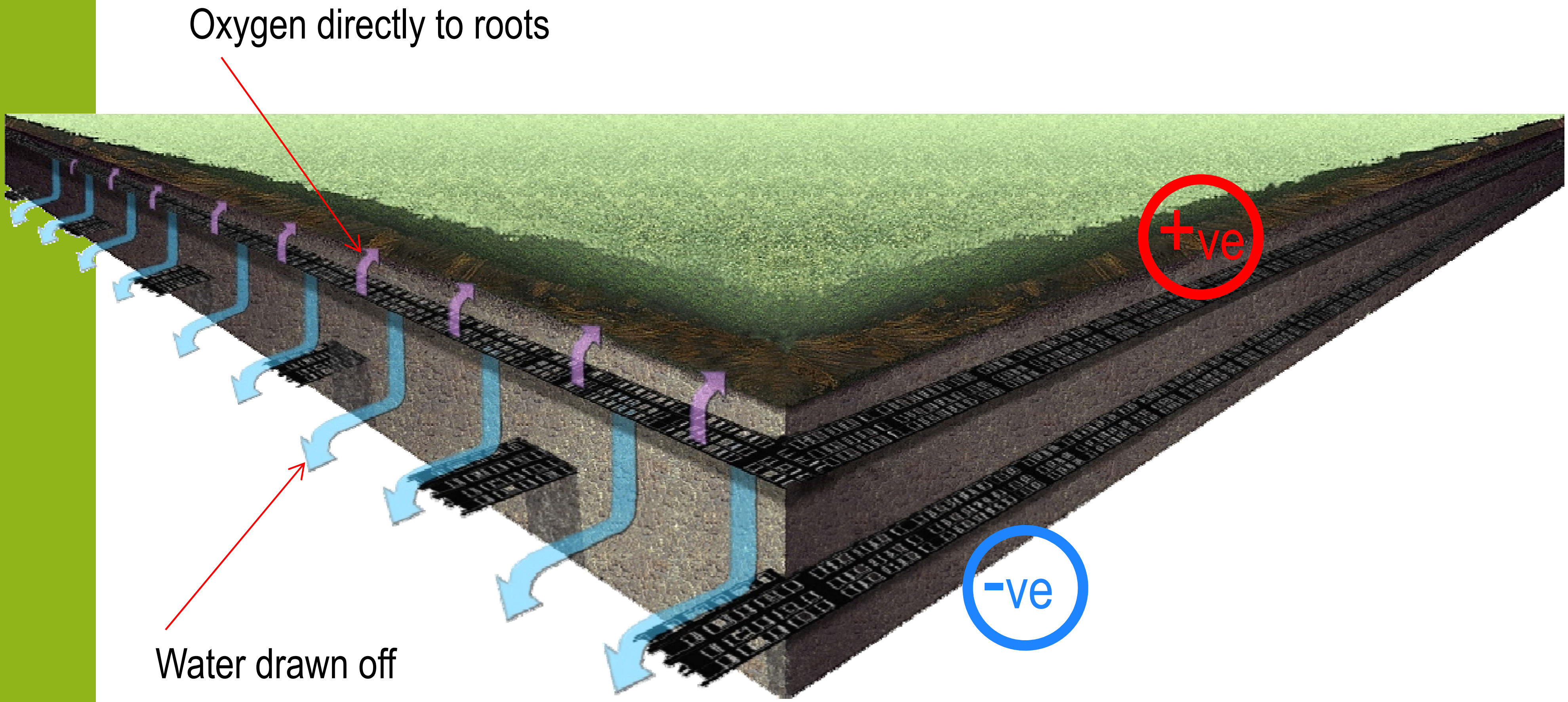


Fill after EK treatment



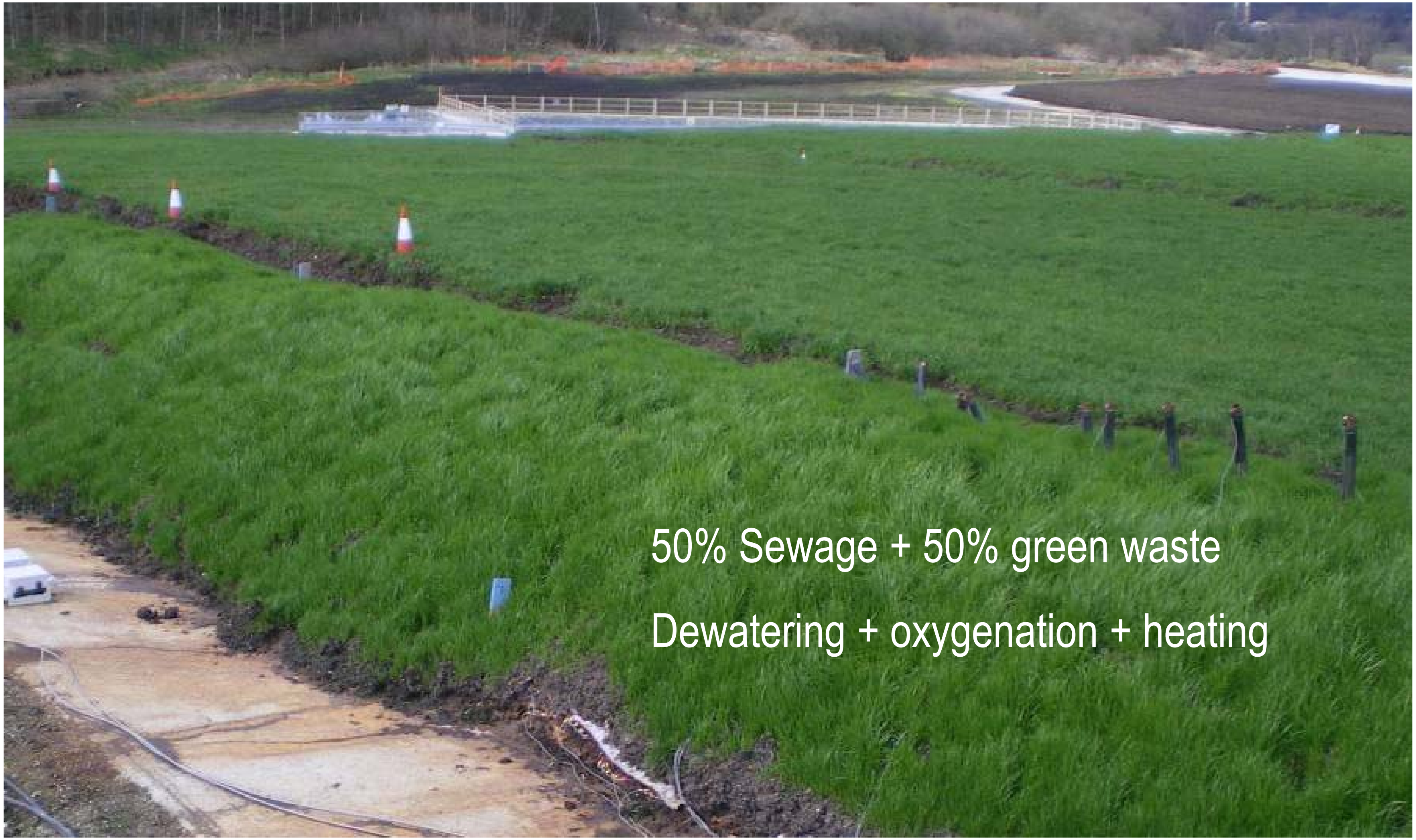
━ Cathode
━ Anode
- - - Secondary reinforcement

Possible applications – sports turf (rejected)


Oxygen directly to roots

Water drawn off

Possible applications – waste/composting rejected



50% Sewage + 50% green waste

Dewatering + oxygenation + heating

In abeyance - dewatering of mine tailings - SA

55% reduction in carbon dioxide

55% reduction in power consumption

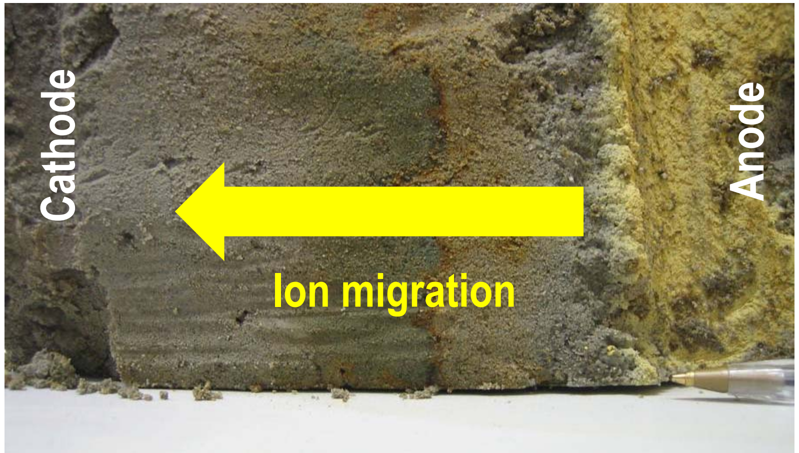
67% reduction in water discard

49% reduction in volume of tailings

Transportable by conveyor

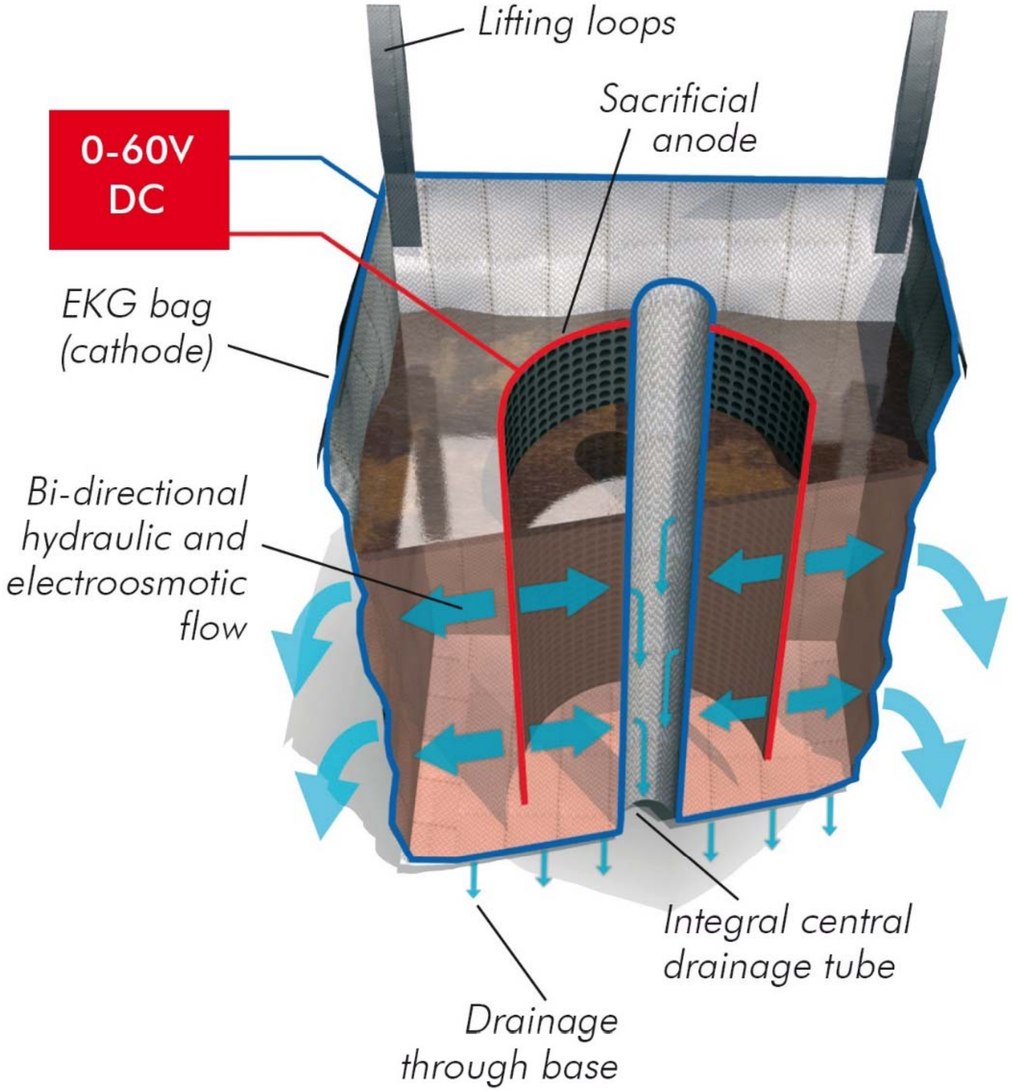
Need for tailings dam?

Reduction of liquefaction potential – Utah, in abeyance



Current applications of electrokinetic technology

Dewatering using EKG bags



- Drilling wastes
- Slurry waste
- Nuclear waste

Dewatering using EKG bags

Initial 2%

EKG bag

Non EK dewatering 8% ds

EK dewatering 20-30% ds

Dewatering of nuclear contaminated slurry & drilling waste

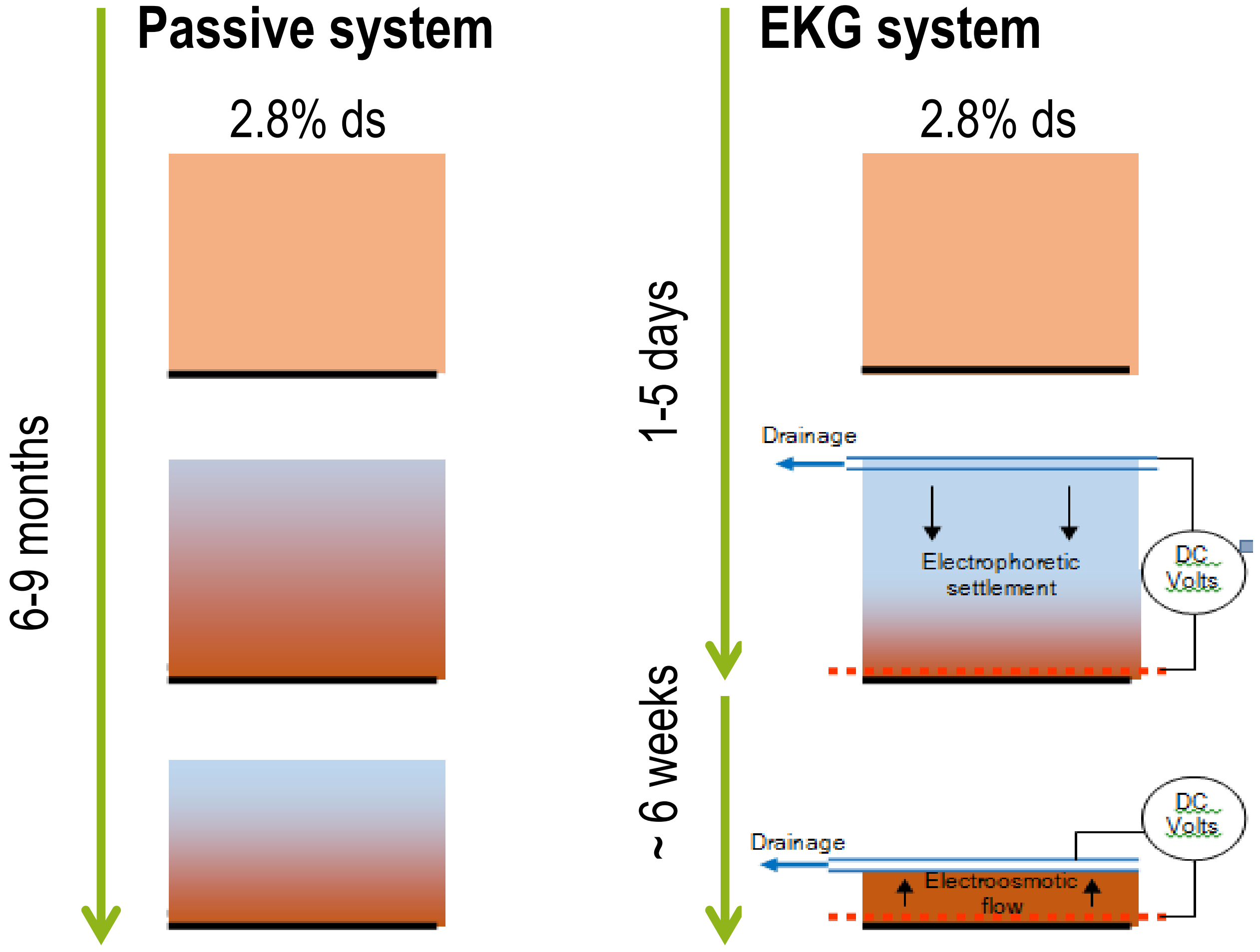
Nuclear waste 90% reduction in volume

Solidification of drilling mud

Dewatering of coal mine waste – (ochre)

- A legacy from centuries of mining
- Material is initially in the form of a suspension
- Conventional treatment – allow to settle in a shallow lagoon, decant water and dry out residual sludge

Dewatering of lagoon waste



Passive system

2.8% ds

Maximum solids content ~ 6 – 9% achieved by gravity settlement

6-9% ds

EKG system

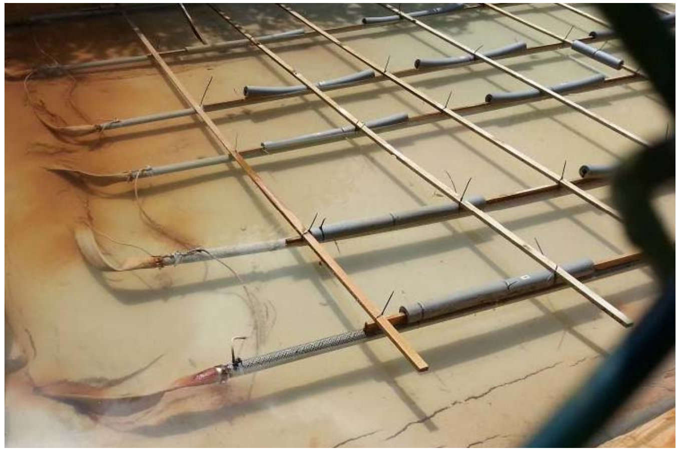
2.8% ds

Maximum solids content ~ 20 – 30% EP accelerated settlement and EO consolidation

20-30% ds

Dewatering of mine waste

Initial condition



Clarification by electrophoresis in 1-5 days

EKG cathodes on top of orches sludge - drying by electroosmosis

Dewatering - China

Electrodes - Chinese EKG strip (Mk 4)

Lagoon dewatering

Large number of lagoons some over 200 years old

Sludge – “too thick to pump too thin to shovel”

Sludge has to be solidified before disposal

Dewatering active treatment – 6 weeks

Northumbrian Water sludge lagoon

Electrodes installed by hand

Consolidation of dredged silt/clay - China

Dredging and hydraulic filling is an important method for land reclamation

Conventional treatment – vacuum or surcharge loading

Vacuum consolidation – 6-12 months effective to a depth of 1-2m for machines to work on - secondary treatment is required (piles)

Surcharge loading – 3 years to produce same effect as electrokinetic treatment

Electrokinetic treatment

Electrode based on
Mk 4 EKG
Price = 20RMB/m
(~3USD/m)

20 days of treatment, 16 days of intermittence

Energy consumption 5.6 kwh/m^3

Water content: 62%→36%

Unconsolidated-undrained shear strength: 0→25kPa

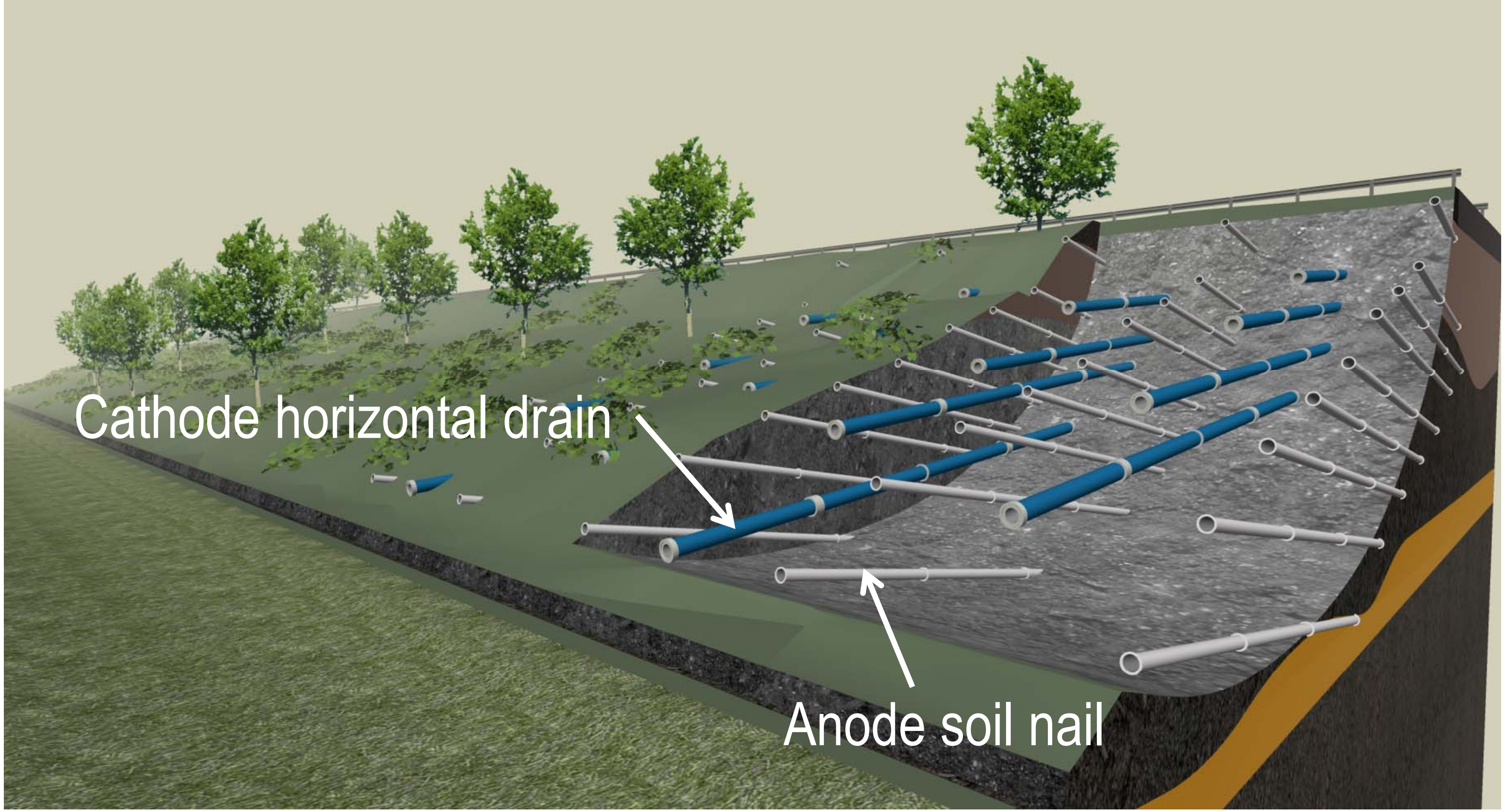
Bearing capacity: 0→70kPa (Target 80kPa)

Design based on electrical accumulation theory or electrical level gradient theory

Electrokinetic slope stabilisation

Components

Electrodes in the form of cathode drains and anode soil nails



EKG slope stabilisation has 4 components

Electroosmotic ground improvement

Reinforcement

Drainage

Soil modification

Remedial actions are distributed across these effects

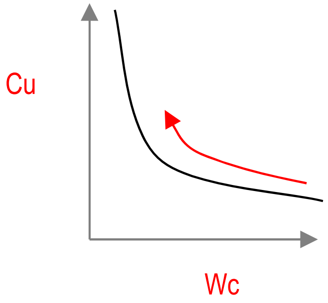
Intensity of actions is dominated by:

- Electrode array
- Treatment duration

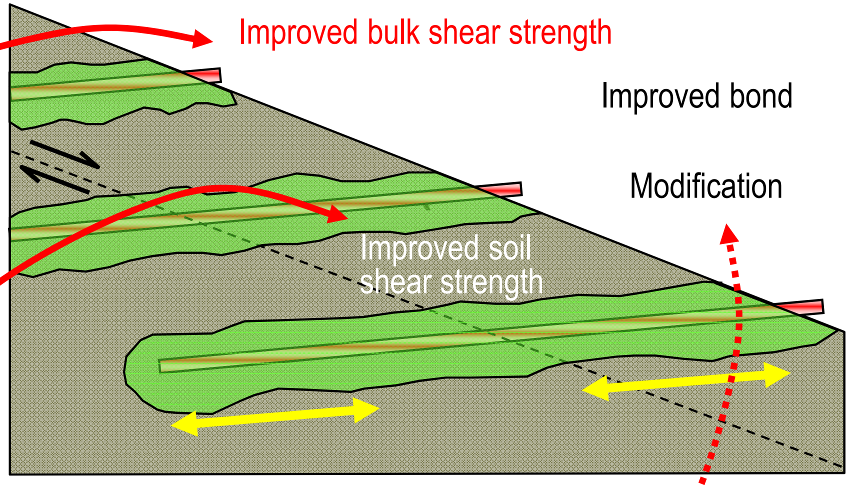
EKG slope stabilization has 4 components

1. **EO ground improvement**

Shear strength improvement c’ phi’ and changes to plasticity index

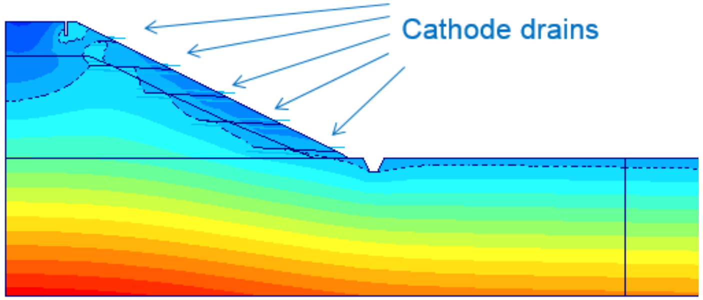


2. **Reinforcement**



3. **Drainage**

Reduced pore pressure by passive cathode drainage

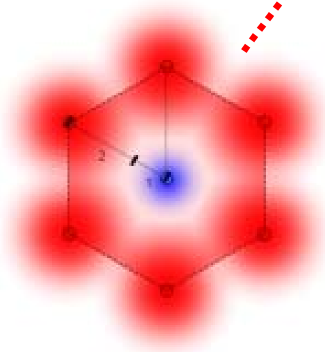


4. **Soil modification**

Conditioner Ca^{2+}

Cation exchange

Improved EO flow



Electrokinetic slope stabilisation

Design

Design

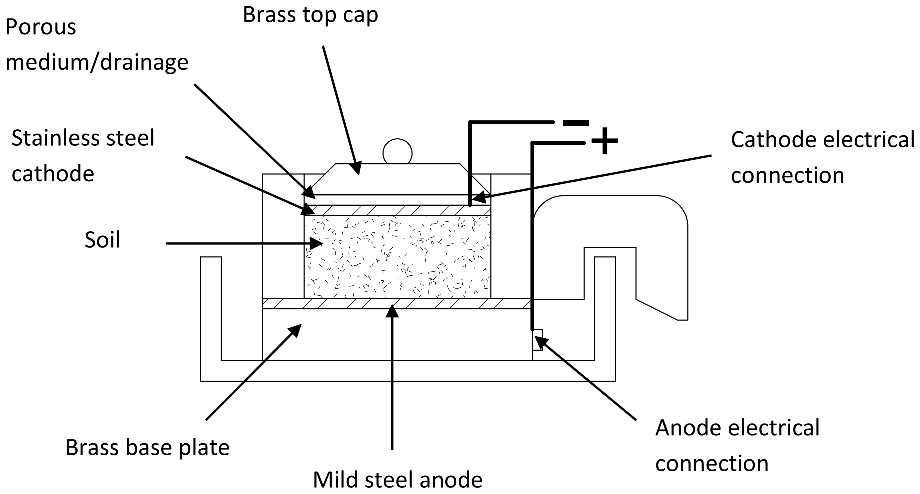
Based upon BS 8006-2:2011 soil nail design

Electrokinetic information required for design

- Electrical conductivity E_c (BS 1377-3:1990)
- Coefficient of electroosmotic permeability k_e (Helmholz-Smoluchowski 1914)
- Electroosmotic consolidation EO (Rosli cell – modified triaxial)
- Increase in anode/soil nail bond strength (Electrokinetic shear box)

Anodic effects of EKG – cementation and increased bond

Ion migration for anode

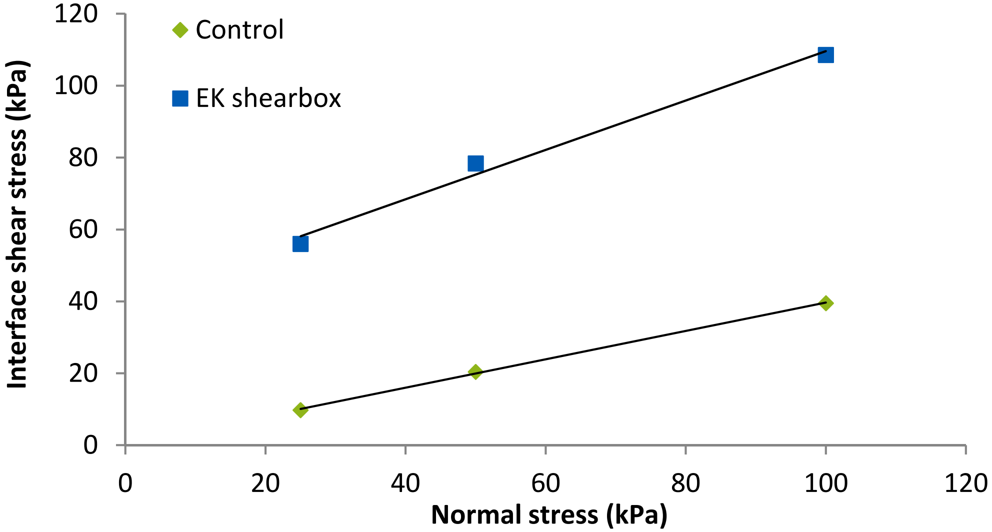


Pre-treatment

c’ = 0kPa, Φ’ = 21.5 degrees

Post treatment

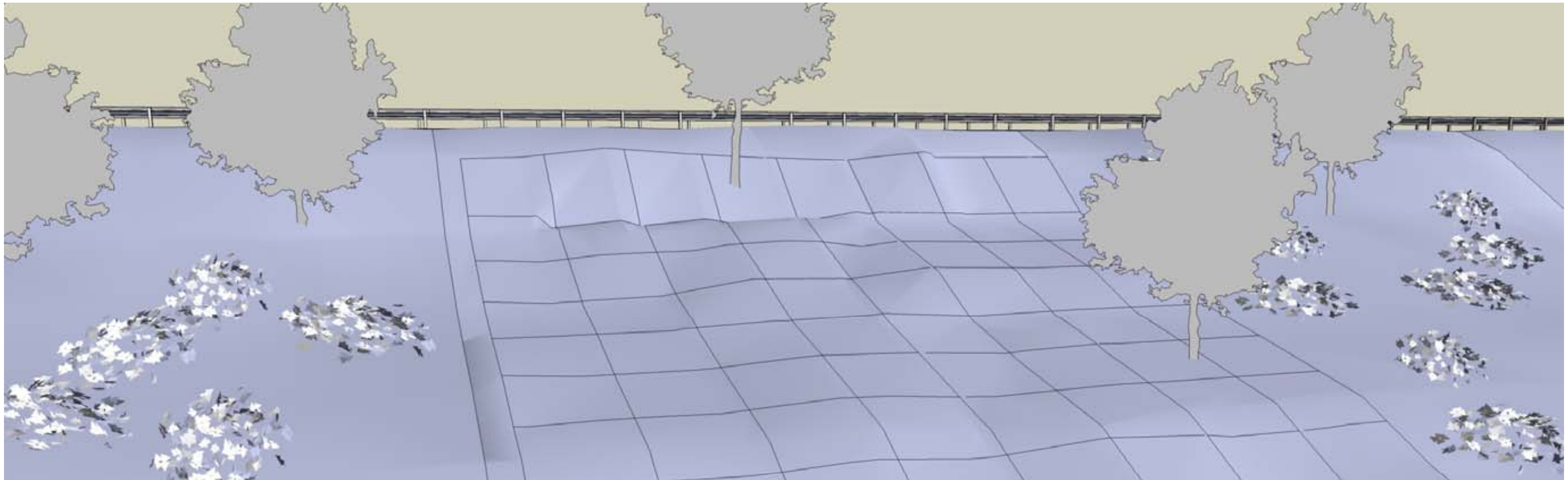
c’ = 40.9kPa, Φ’ = 34.5 degrees



Electrokinetic slope stabilisation

Construction sequence

Clear undergrowth and trim low lying tree branches

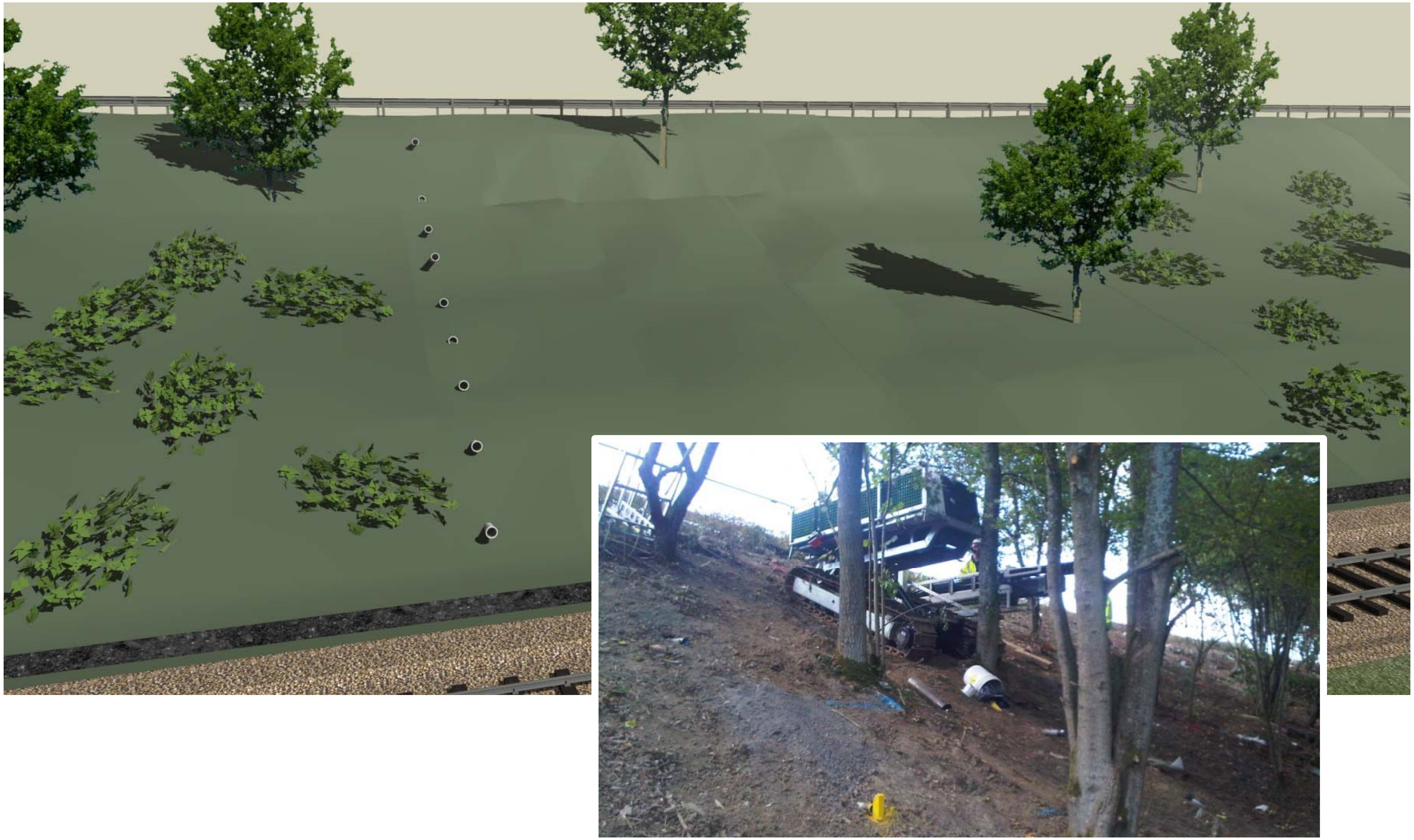


Site before

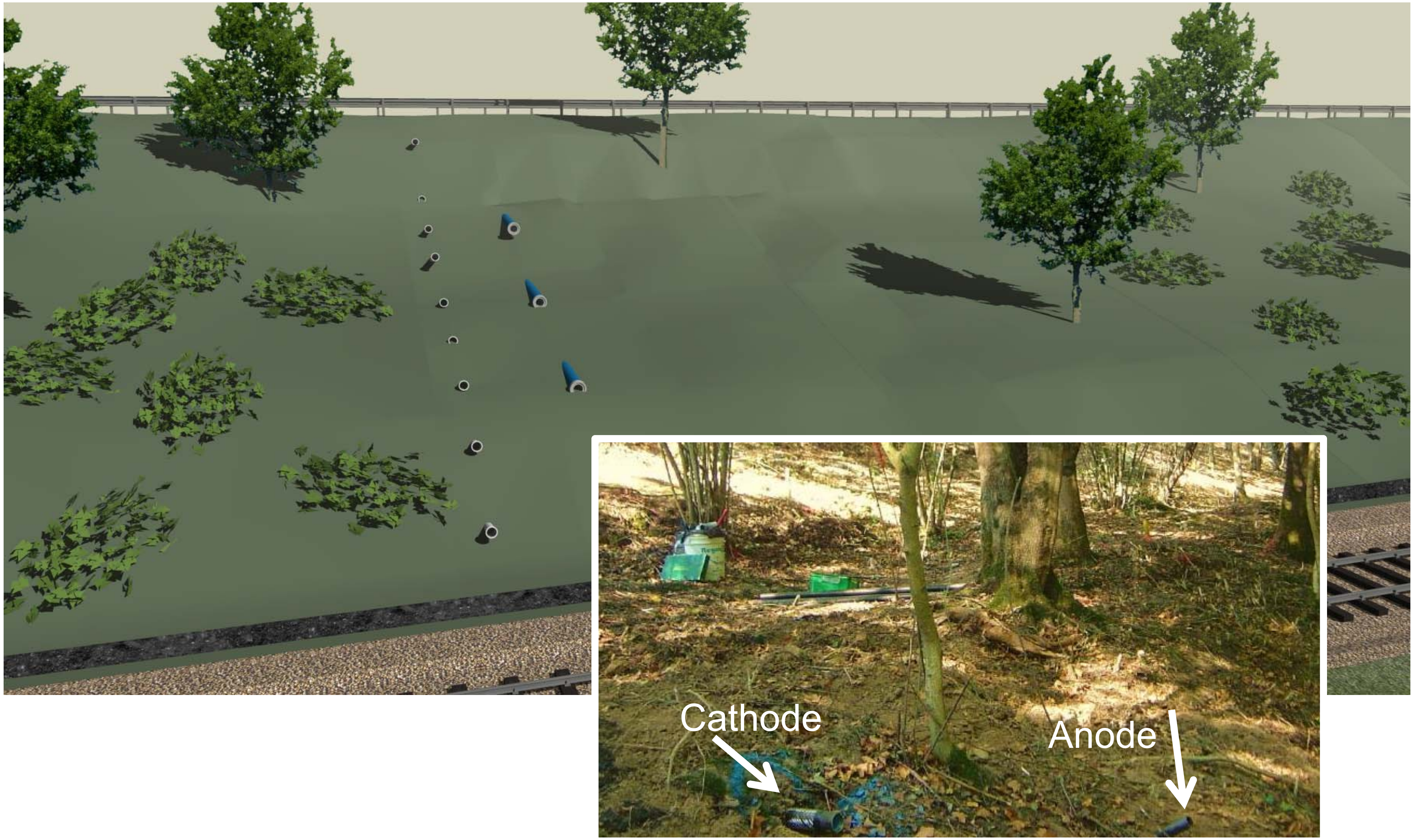
Site prepared for EKG

Site prepared soil nails

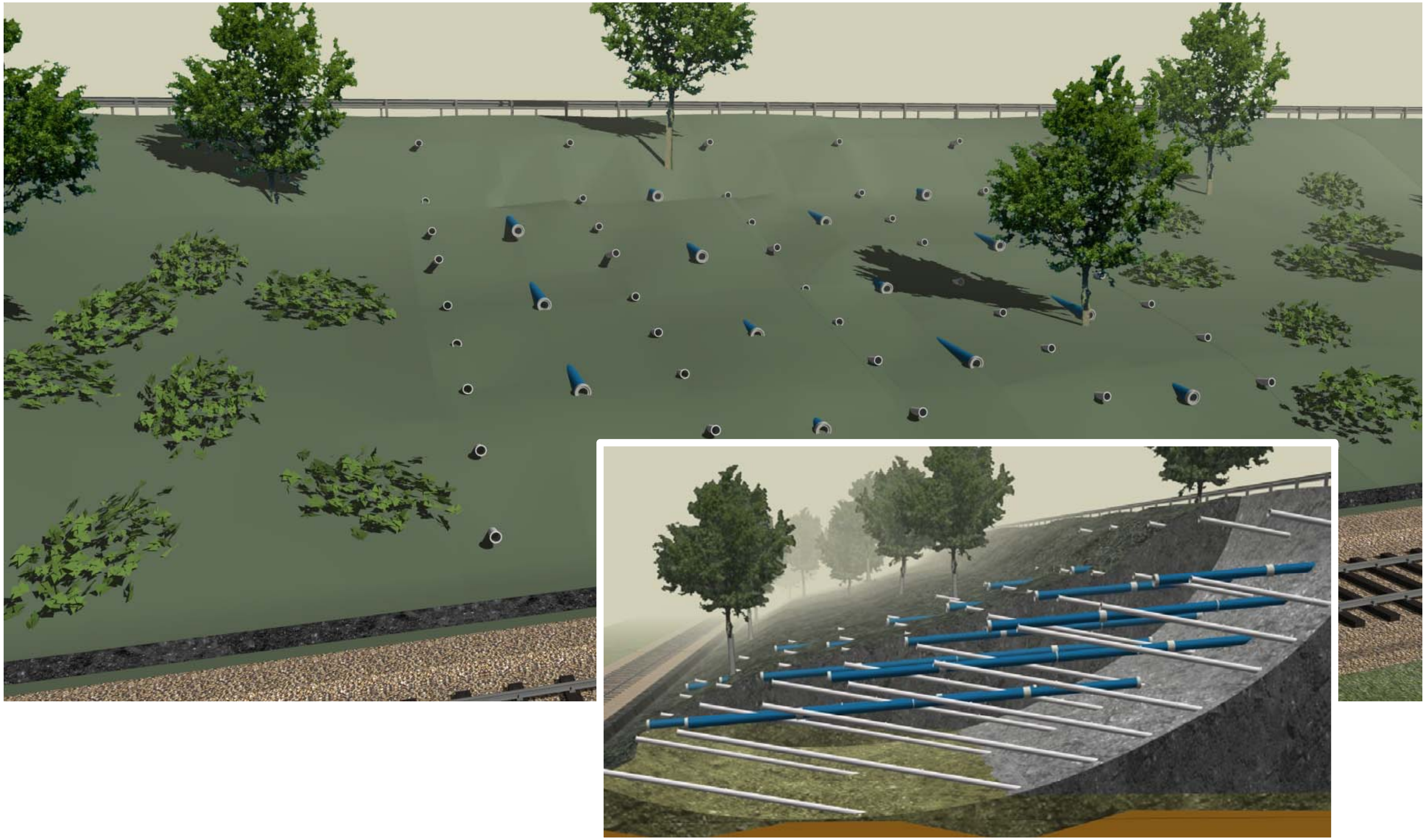
Install anodes and cathodes in alternating gradient-aligned columns



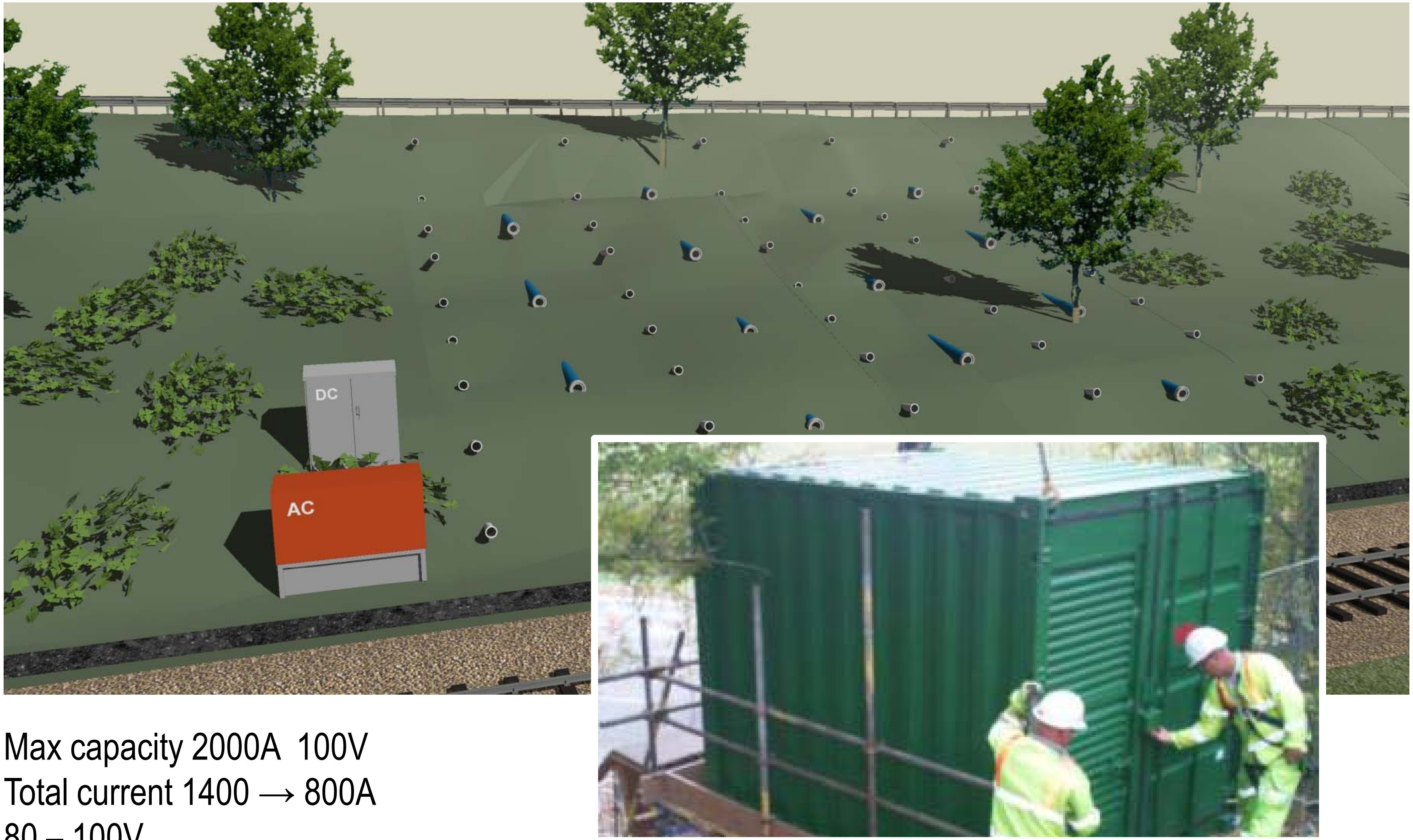
Advance the installation laterally along the slope



Electrode array ready for activation

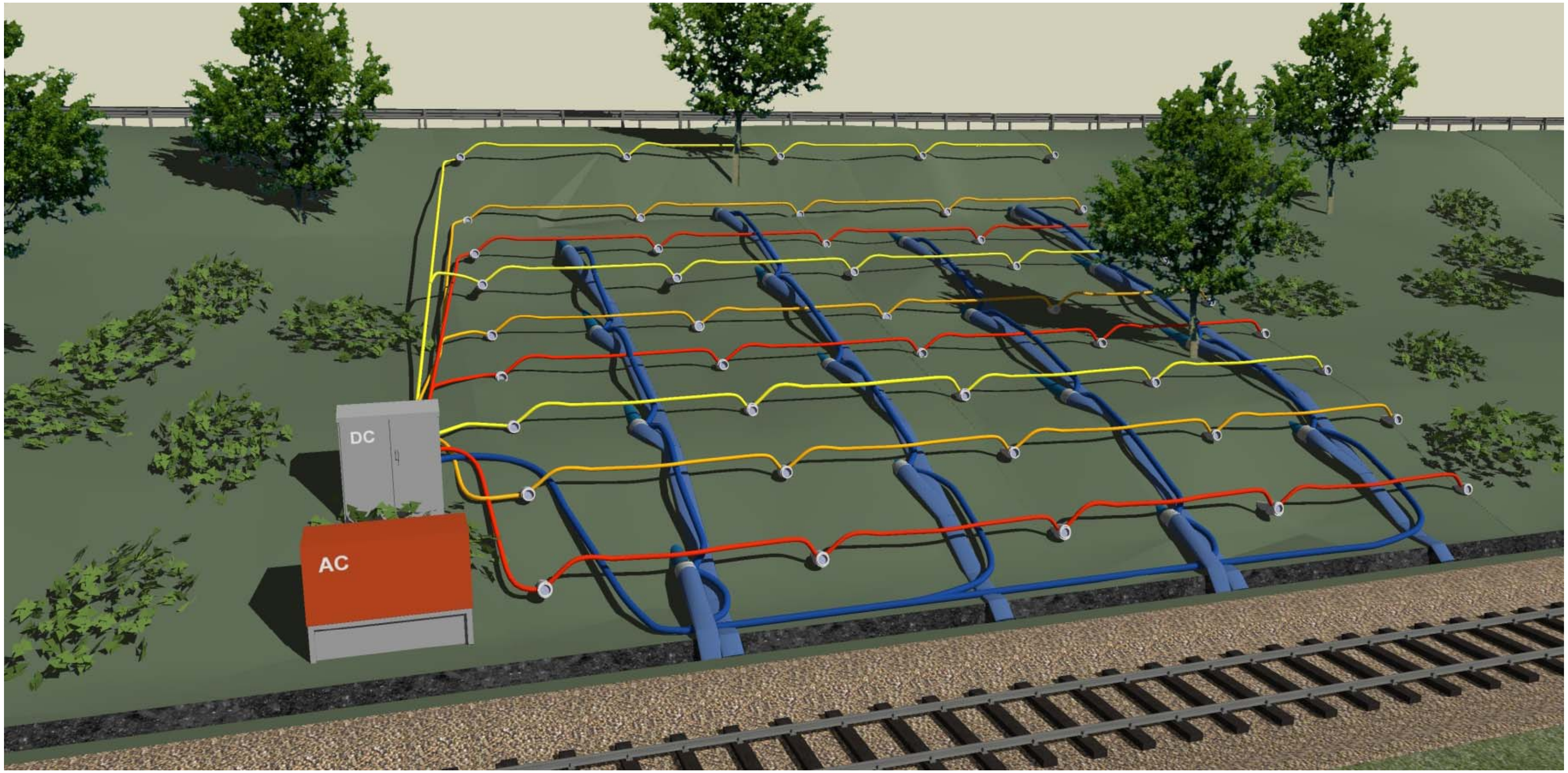


DC power supply



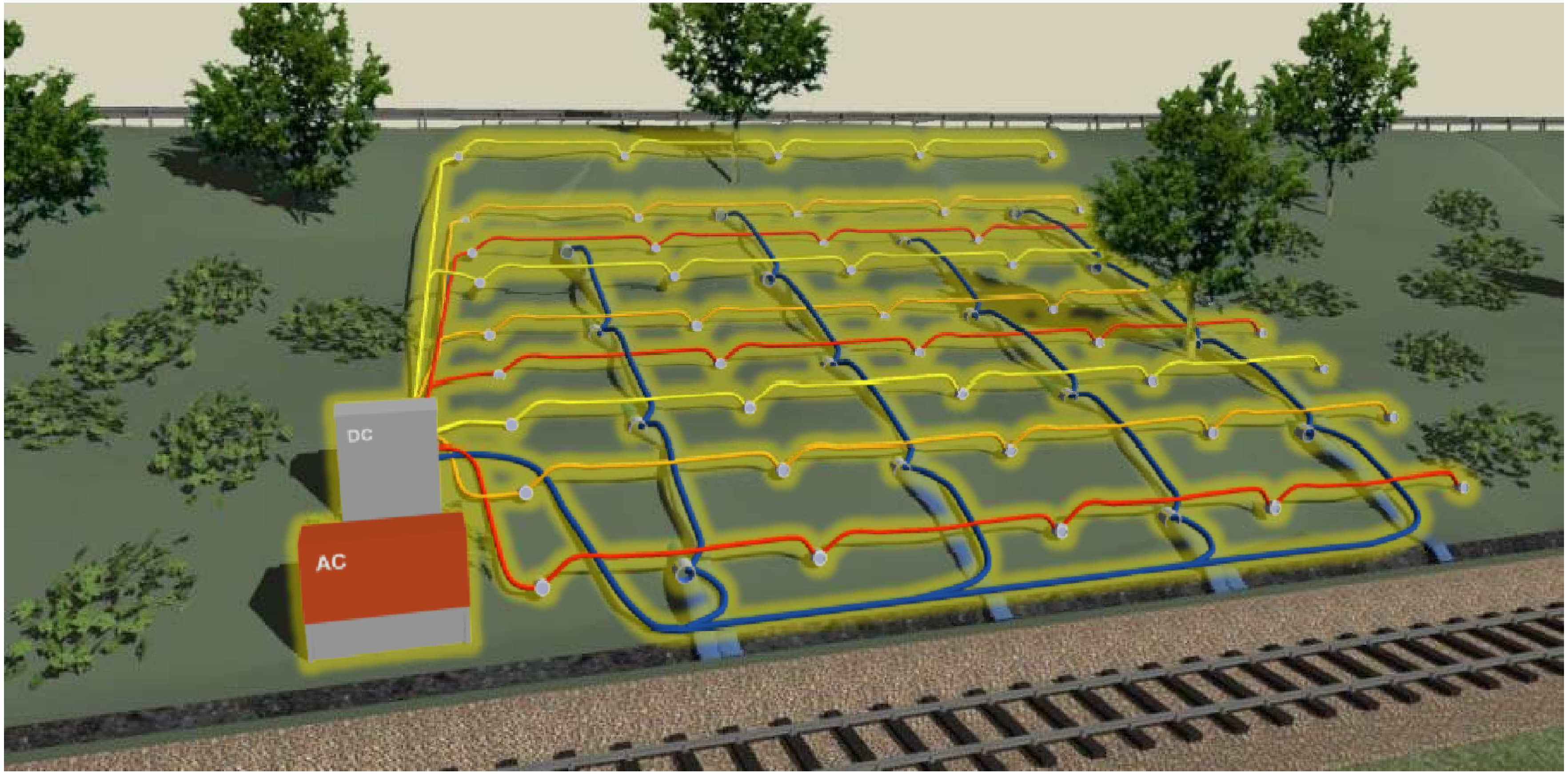
Max capacity 2000A 100V
Total current 1400 → 800A
80 – 100V
3 switchable ‘half circuits’

3 Half circuits – drainage using lay-flay hose

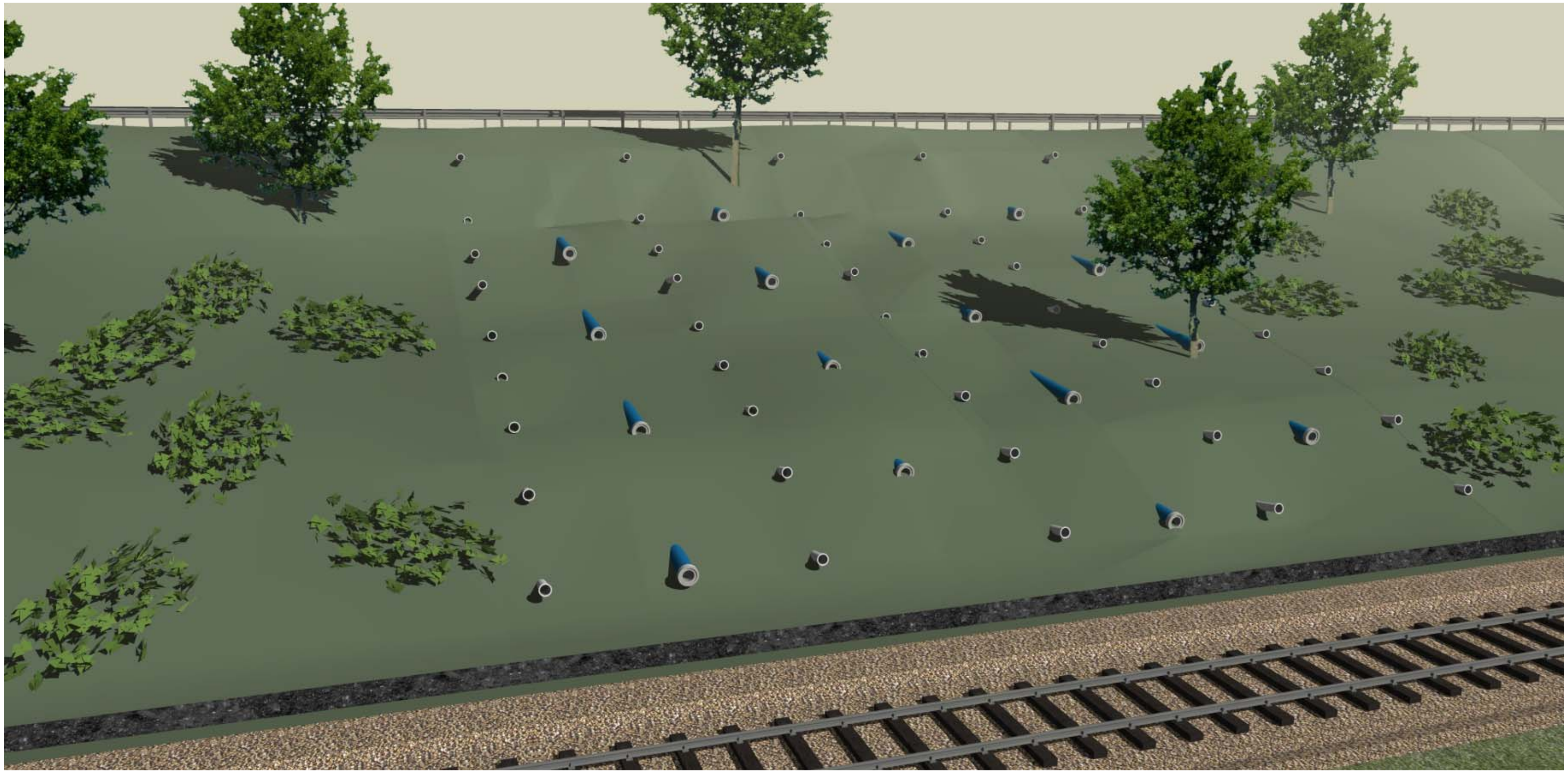


Max capacity 2000A 100V
Total current 1400 → 800A
80 – 100V
3 switchable ‘half circuits’

Electrokinetic activation – 6-8 weeks (no labour requirement)

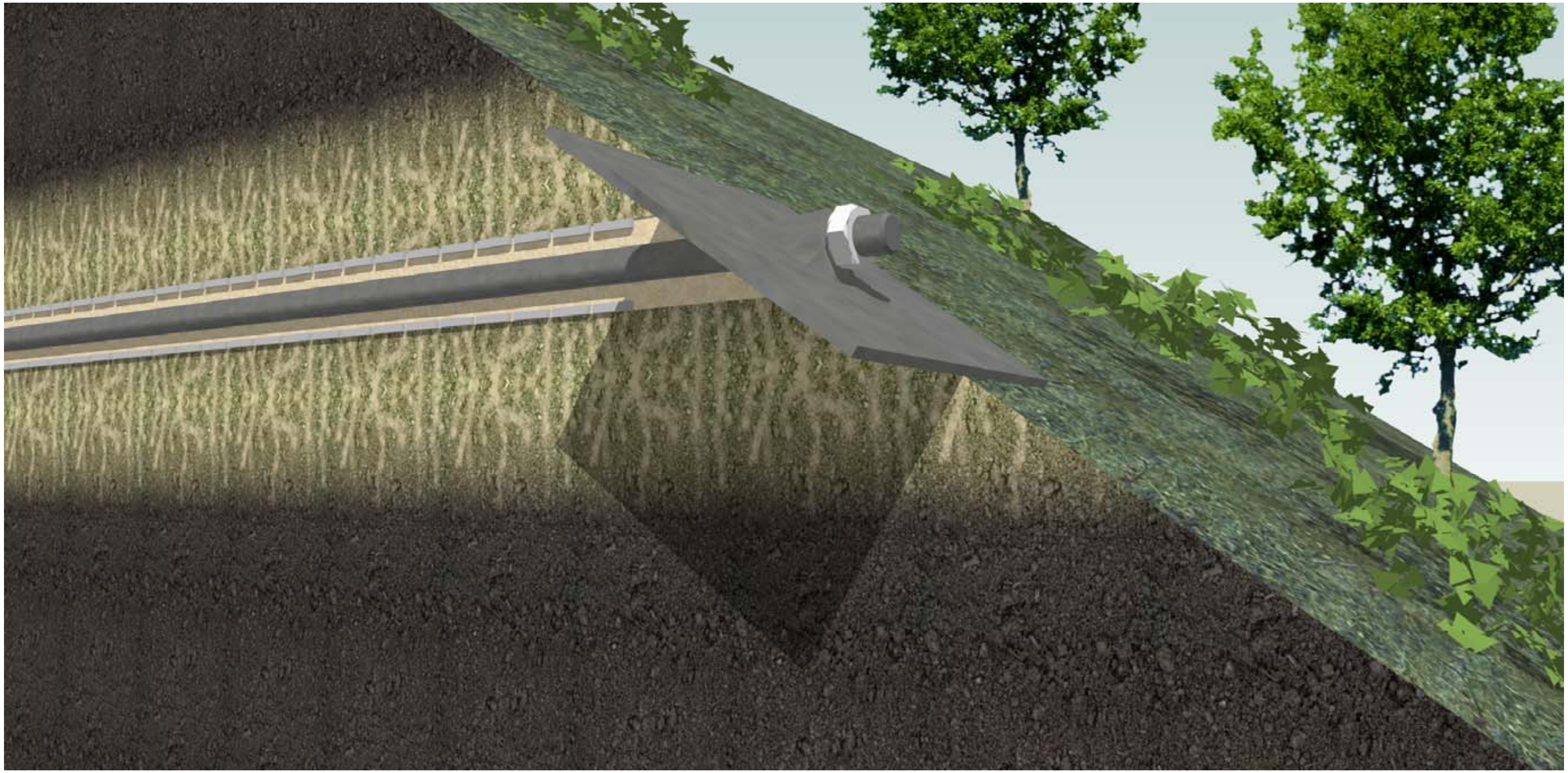


Post EK treatment – array of nails and drains throughout the slope

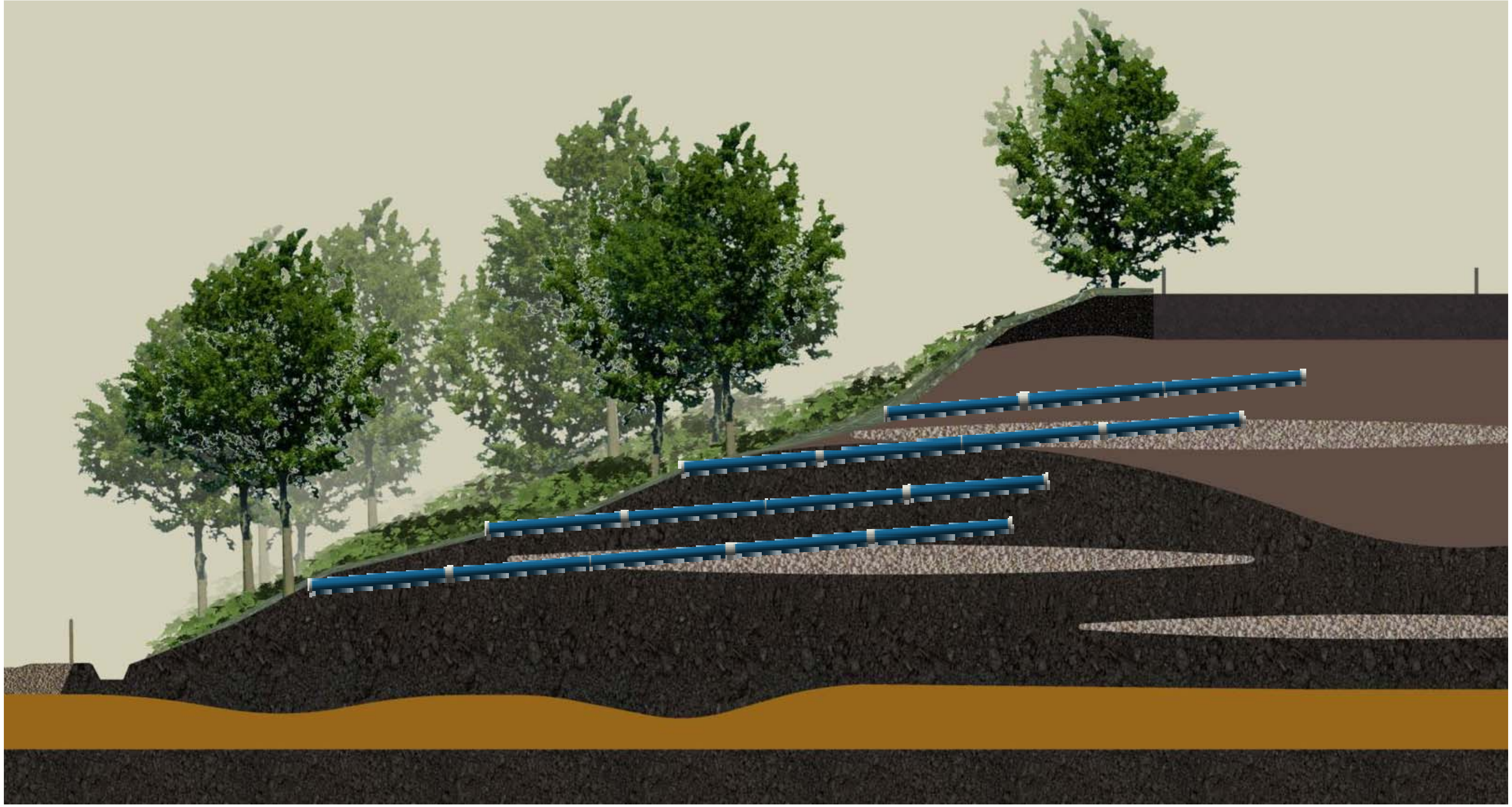


ELECTROKINETIC

Rebar grouted into anodes to convert to soil nails



Cathodes retained as permanent drains



Electrokinetic slope stabilisation

Verification

Verification

Required

- Current monitoring
- Load testing of anode soil nails

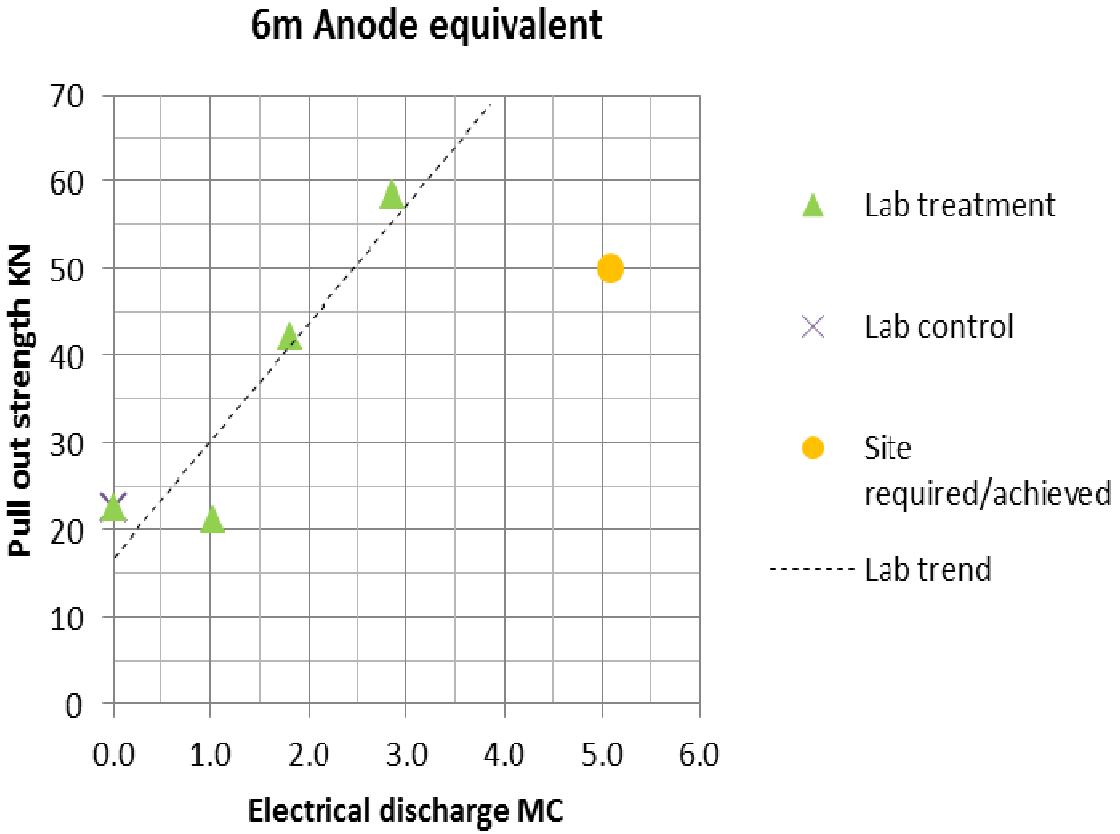
Optional

- Inclinometer data
- Monitoring water discharge from cathode drains
- In-situ strength testing i.e. CPT
- Ex-situ methods i.e. triaxial testing to confirm c', Φ', c_u

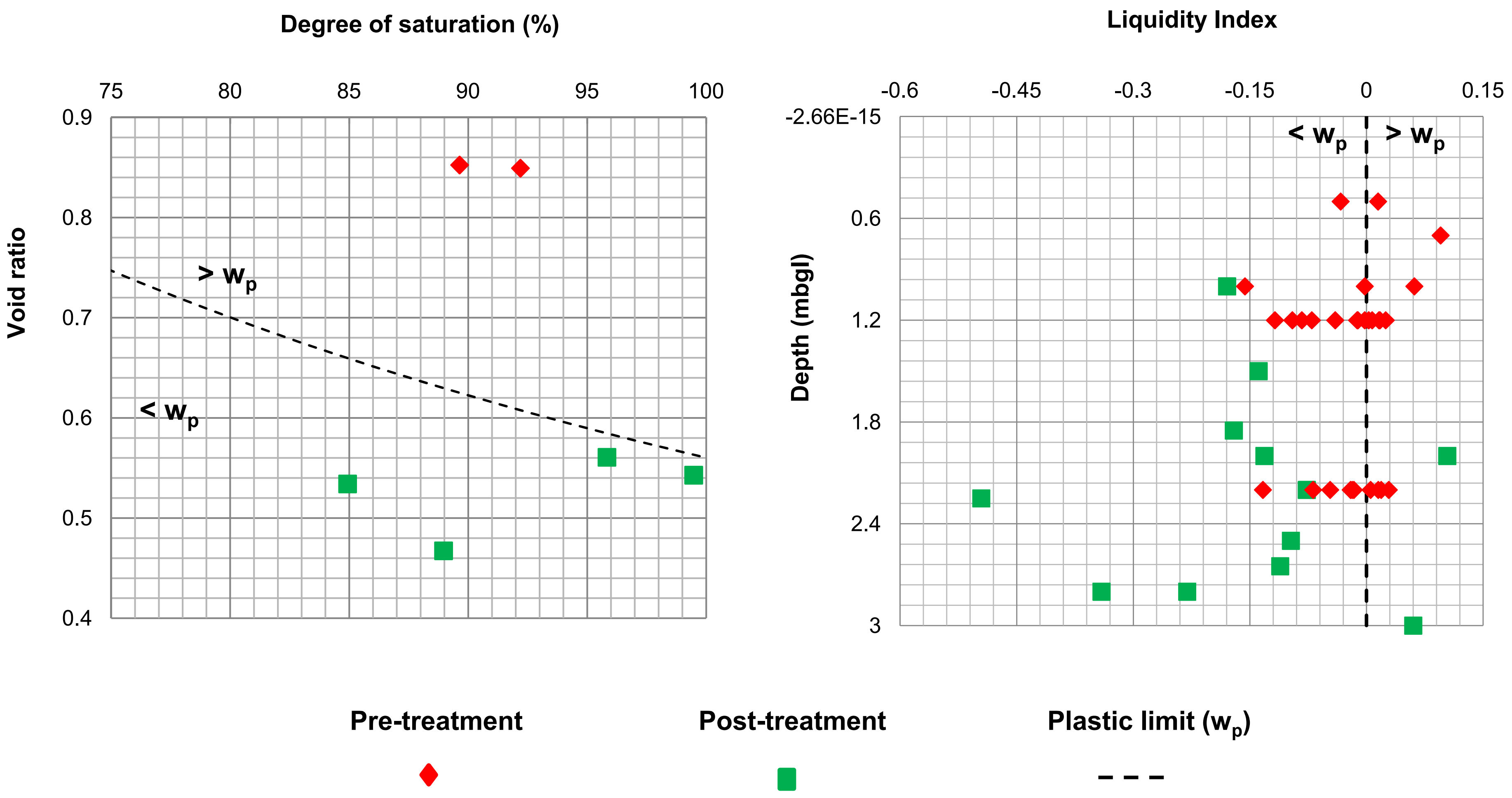
Current monitoring

Development of pull out/bond strength = *f* (electrical charge)

Development of bulk soil improvements = *f* (electrical energy)



Longevity of ground improvement



Electrokinetic slope stabilisation

Case studies

ELECTROKINETIC

Network Rail South Greenford

Victorian, London Clay, 7m high

Inclinometers 50mm/yr

Deep circular failure

6 week treatment

NO LINE POSESSION

Cessation of movement

Electroosmotic drainage:control = 25:1

26% cost saving

47% reduction in carbon footprint

A21 Stocks Green –Weald clay

Weald clay, failing embankment

Mature trees and a rich wildlife habitat (dormouse)

LOW ENVIRONMENTAL IMPACT

Vegetation and natural habitat preserved

29% cost reduction compared to soil nailing on adjacent site

Reduction of 40% in carbon footprint

Requirement for traffic management eliminated

GREEN APPLE ENVIRONMENT AWARD WINNER

ice award winner

HIGHWAYS AGENCY

ELECTROKINETIC

M5 J7 – Lias clay & Mercia mudstone

Variable design: treated in 6 sections

Summer 2012 very wet weather

Soils tests after 18 months:

ZERO DISRUPTION TO TRAFFIC

9% cost saving and 43% reduction in carbon footprint

Improvement in drained and undrained shear strength

A419 Swindon – Oxford clay

Shallow circular failure

Oxford Clay embankment

Previous granular replacement

VERY LOW IMPACT CONSTRUCTION

Installation 3 workers – 3 days

No earthworks and zero waste

Connection 2 workers – 2 days

6 weeks active treatment

Reinforcement 3 workers – 3 hrs

Decommission site – 4 hrs

SLC A72 Upper Clyde Valley –Glacial material

Sidelong embankment and cutting

Electrodes up to 21m long
Installation yields dynamic probe data
Continual update of ground model

GCC English Bicknor, Forest of Dean

Shallow circular failure

Deeply weathered mudstones

Sidelong embankment
at / below water table

DIFFICULT GROUND CONDITIONS

Installation 3 weeks

No earthworks and zero waste

Designed in 3 zones

Implementation of the ‘observational method’

Road re-build during active works

Economic and environmental benefits

EKG slope project	Alternative solution	Cost saving	Reduction in embodied CO_2
Network Rail, Ealing	Gabion baskets and regrade	26%*	47%*
A21, Kent	Soil nailing	29%*	40%*
M5, Worcester	Soil nailing	9%	43%*
A419, Swindon	Reinforced soil	35%*	35%*

* Meet the objectives of Construction 2025 Industrial Strategy, BIS (2013)

Further applications

Pore pressure control

ELECTROKINETIC

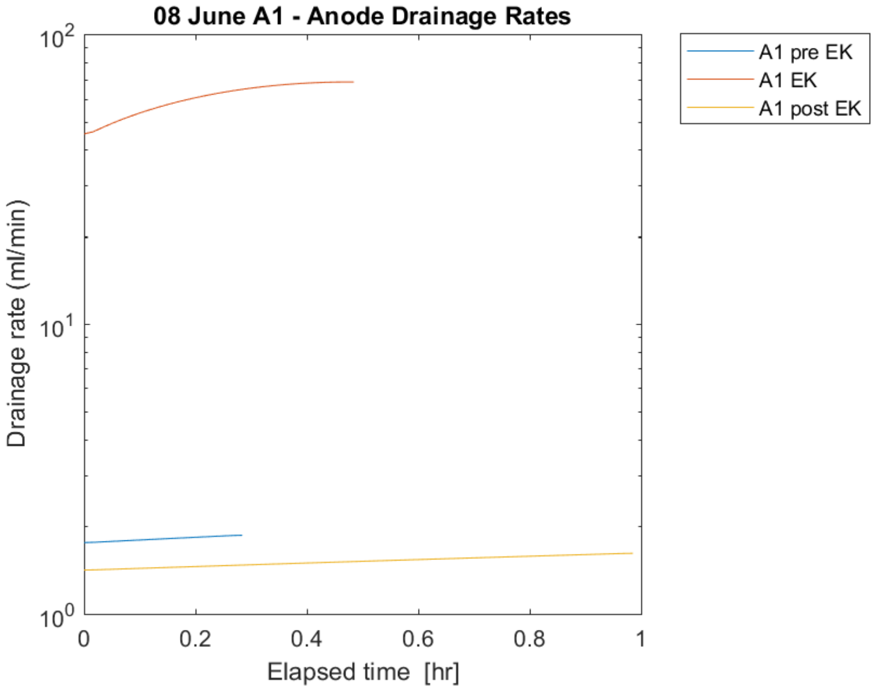
Control of pore water pressure

Esrig (1968) proposed analytical solution for pore pressure change through electroosmosis:

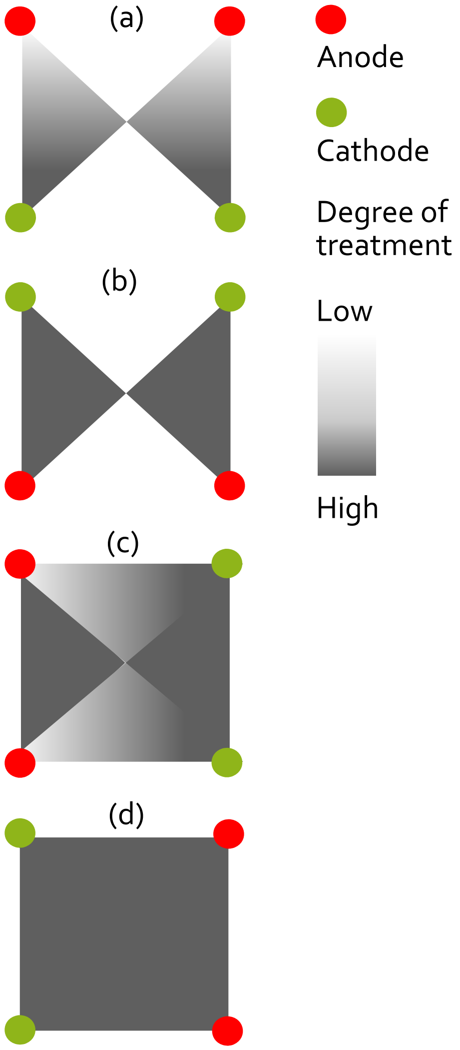
$$u = \frac{k_e}{k_h}\gamma_w V(x) + \lambda\frac{2k_e\gamma_w V_m}{k_h\pi^2} \bullet \sum_{n=0}^{\infty}\frac{-1^n}{\left(n+\frac{1}{2}\right)^2} sin\left[\frac{\left(n+\frac{1}{2}\right)\pi x}{L}\right] \bullet exp\left[-\left(n+\frac{1}{2}\right)^2 \pi^2 T_v\right]$$

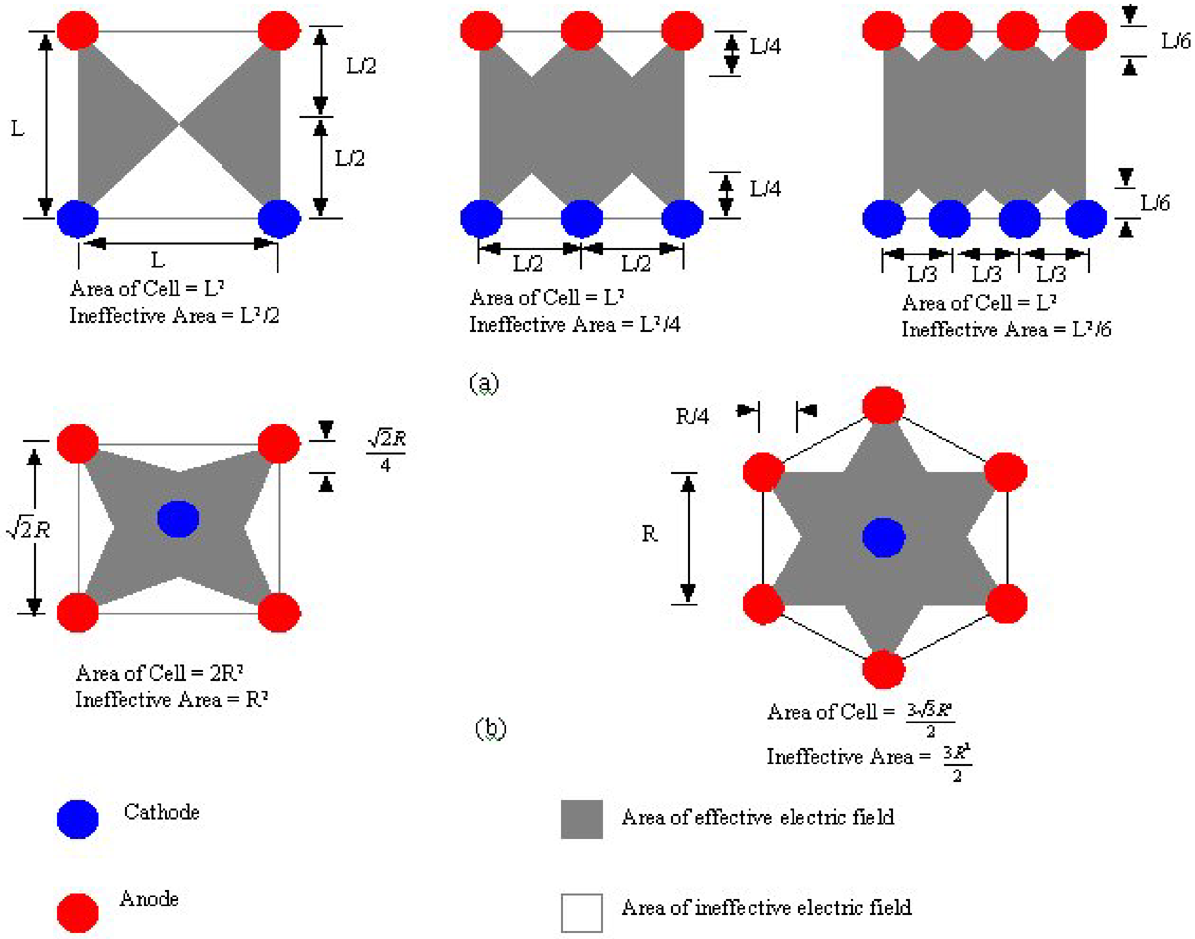
Able to analyse positive or negative pore pressure changes

Volume control applications



Control of pore water pressure





Further applications

Electroosmotic chemical treatment

Electroosmotic Chemical Treatment (ECT)

Concept is to enhance electrochemical changes by introducing a conditioner into the soil using electromigration and electroosmosis.

Main effect is cation exchange. Other processes include:

- Cementitious precipitation
    - Managed electrode corrosion
    - Combining chemical conditioners
- Ion Fixation

Generally EM ≥ 7x faster than EO

Achieves similar results to lime modification but without the need for mechanical mixing

Examples of ECT

Chien et al (2010) used ECT with $CaCl_2$ & Na_2SiO_3

(readily available & inexpensive conditioners)

Reactions

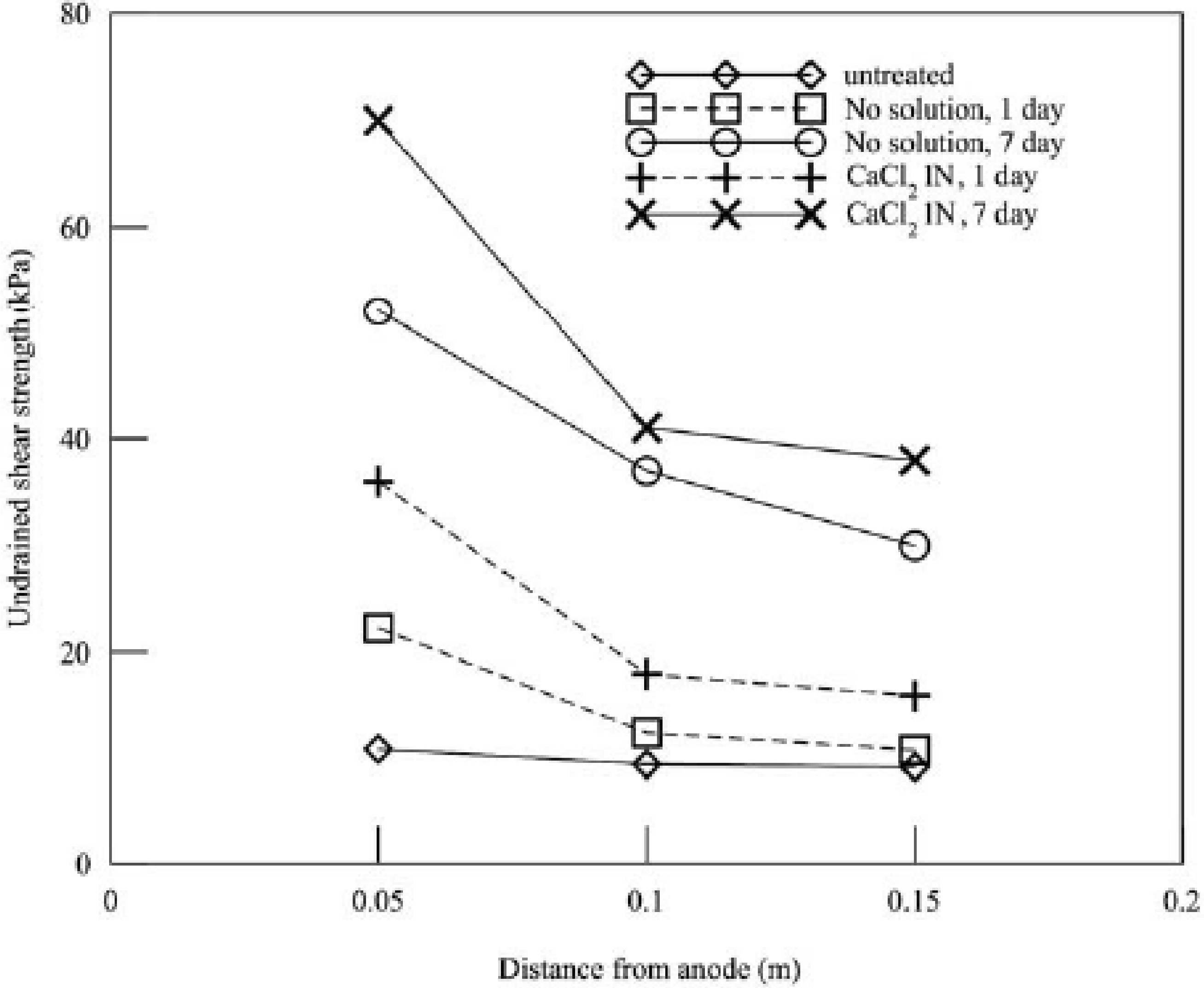
$CaCl_2 + Na_2SiO_3 + H_2O \rightarrow [Ca\,SiO_3].\,H_2O$ ppt

$Ca^{2+} + 2OH^- \rightarrow Ca(OH)_2$ gel

EKL have noted 13x increase in anode nail pull out strength using $CaCl_2$ + 40% increase in EO velocity

Electrochemical increase in shear strength

Chien et al. (2010)



Electroosmotic Chemical Treatment (ECT)

Abdullah and Al-Abadi (2010)

Results on highly expansive clay of montmorillonite, mixed layer illite/smectite and minor kaolinite:

Conditioner	**Plasticity index (%)**		**Swelling potential (%)**		**Φ' (degrees)**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
Calcium hydroxide	40	31-34	14	3	24	31
Calcium chloride		32-33				
Potassium hydroxide		8-32		0.4	24	36
Potassium chloride		8				

Ion Fixation

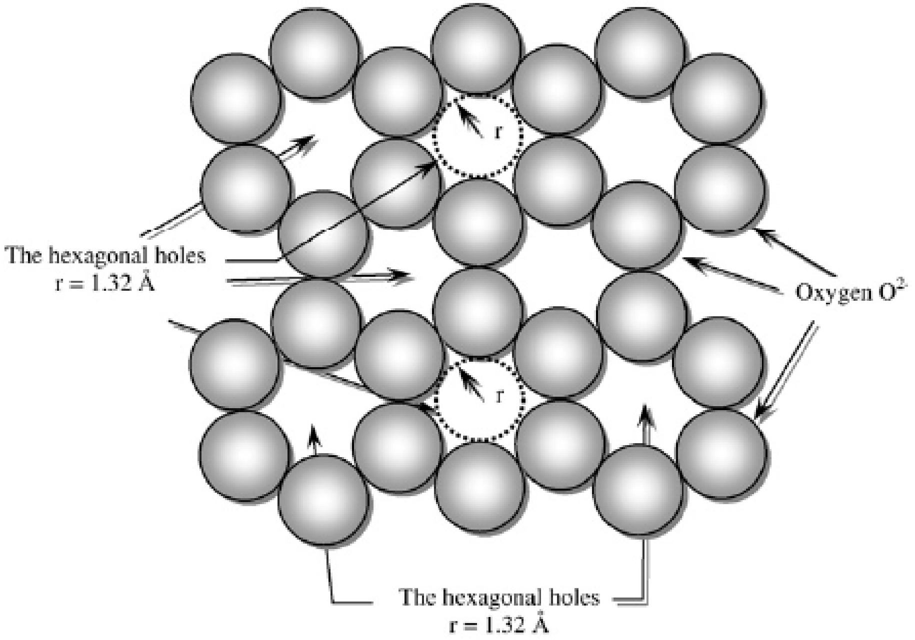
K^+ ions 1.33Å

Hexagonal lattice holes 1.32Å

Produces strong bond between adjacent clay layers

Fixed K^+ is non-replaceable

Smectites have high fixation power, Illites even higher



Electroosmotic Chemical Treatment

Natural hill slope

Mixed glacial clays and silts

200m long 30m high

Failure surface up to 15m below ground level

Summary

Electrokinetic treatment is not new

Development of novel electrodes and computer controlled application overcomes past deficiencies

Electroosmosis accepted in BS 8006-2:2011 Soil nail design

Verifiable design

Significant commercial and environmental benefits

Increased productivity

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References and notes – Why does it cost less?

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

References and notes – Low environmental impact

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