Lecture 14

Electrokinetic Stabilisation

Objectives

- To provide an overview of the electrokinetic process.

- To describe a few field trials of the technique

Electrokinetic Stabilisation

- One of the most common causes of foundation movement is volume change of active clays in response to environmental and/or vegetation, notably clay shrinkage in long dry spells and clay swelling following the removal of large trees and hedges.

- Electrokinetic stabilisation is a technique of applying an electrical current through a soil mass to promote the migration of chemicals from injection points, which are usually the electrodes themselves.

- This technique is particularly suited to weak clayey soils that require strengthening and yet possess a low hydraulic conductivity, thus preventing the economic introduction of chemical grout using conventional hydraulic means.

Electroosmosis

- When an electrical potential difference is applied across a soil mass, cations and anions are attracted to the cathode and anode respectively, whereas neutral particles are attracted to neither (Gray and Mitchell, 1967).
- This forced migration occurs most readily by the ions with the greatest mobility.
- Within a soil mass these ions are to be found in the pore water existing between soil particles. The movement of ions within the pore water causes a transfer of momentum to the pore water.

- The corresponding direction and rate of pore water movement are determined by the net transfer of momentum by both cations and anions within the pore water.

- Because of the nature of clay formation, which usually results in significantly negatively charged clay particles, the predominant ions within the pore fluid are cationic and the water therefore moves from the anode to the cathode.

- The two fundamental factors that control the degree of water migration are the *cation : anion distribution* within the pore water and the *water–cation distribution* within the soil.

Cation : Anion Distribution

- Figure 1 illustrates the typical ion distribution for a sodium-saturated smectite immersed in sodium chloride solution.

- The negative surface of the clay particle promotes a high cation : anion ratio within the diffuse water layer, which is adsorbed onto the clay particle, whereas the free water has a much lower cation : anion ratio.

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- A theory explaining the degree to which anions may migrate from the free water into the diffuse water layer, and the associated effects on electroosmosis, was formulated by Donnon (1924). The theory has not been universally accepted as true for all clays, but it has nevertheless proved helpful in understanding the process.

- This aspect is of particular importance as it controls chemical changes, such as pH and adsorbed water content, as well as the physical behaviour of clay.

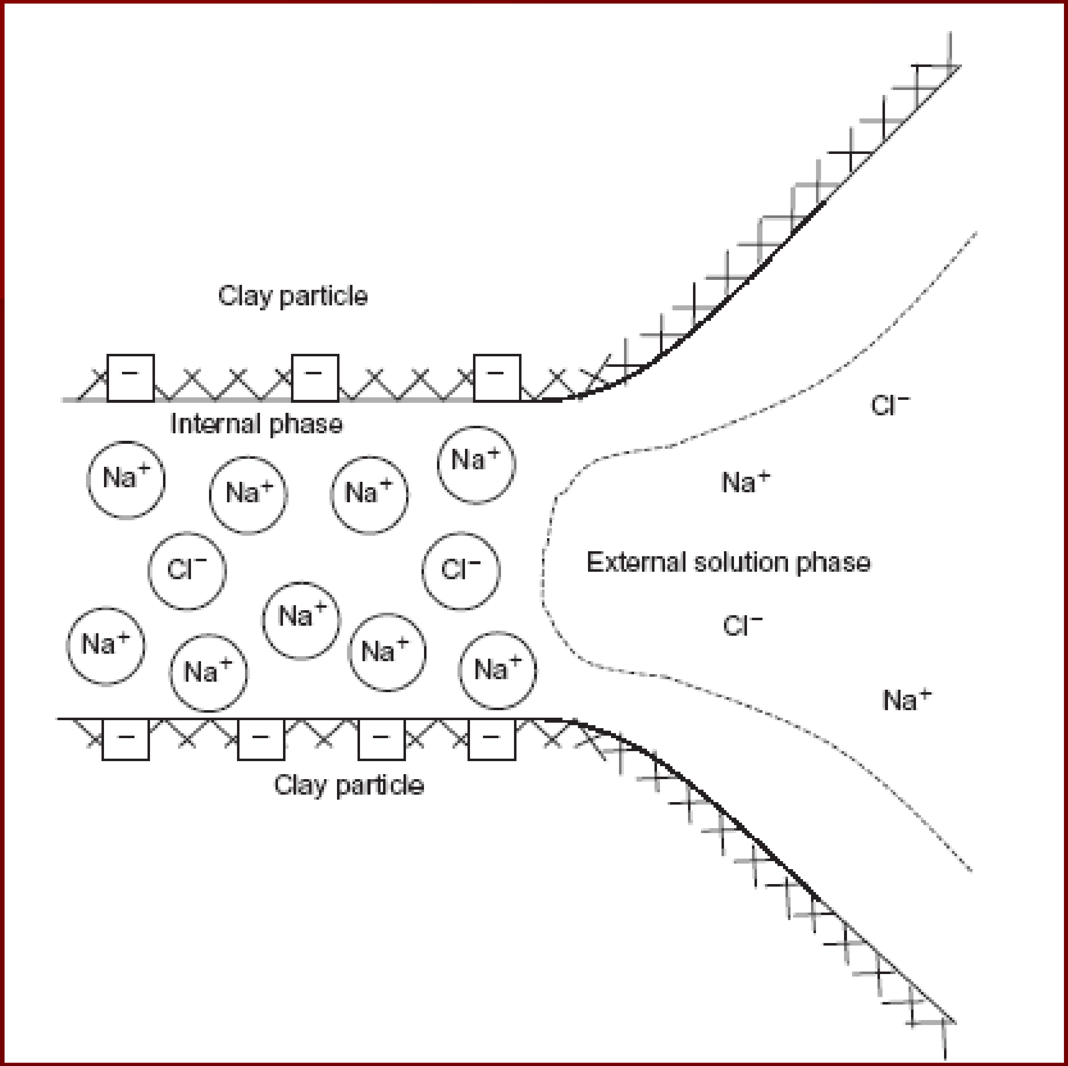


Fig. 1. Typical ion distribution for a sodium clay immersed in sodium chloride solution (after Gray and Mitchell, 1967)

Water : Cation Ratio

- The electroosmotic water flow per unit charge, W, is proportional to the water : cation ratio in the diffuse water layer (Gray and Mitchell, 1967).
- This relationship may be modified to take into account such effects as friction or drag between either the water and solid or water and ion (Spiegler, 1958).
- Thus, in high cation exchange capacity clays with low water contents W will be low, as the water transferred per ion equivalent or quantity of electric charge will be low.

$$W \propto \frac{\text{molar concentration of water}}{\text{molar concentration of cations within diffuse water layer}}$$

- From such relationships it is possible to predict the behaviour of clay, in terms of electroosmotic efficiency, when in different states—that is, having different values of water content, cation exchange capacity and cation : anion ratios between the diffuse water layer and free water system (Fig. 2).

- The terms ‘active’ and ‘inactive clay’ used in Fig. 2 refer effectively to the cation exchange capacity of the clay, which will have a marked influence on the size of the diffuse water layer and hence on the volume of water present within the pore solution available for electroosmotic transport.

- Activity is defined as the ratio of the plasticity index to the percentage of clay-sized particles in the soil.

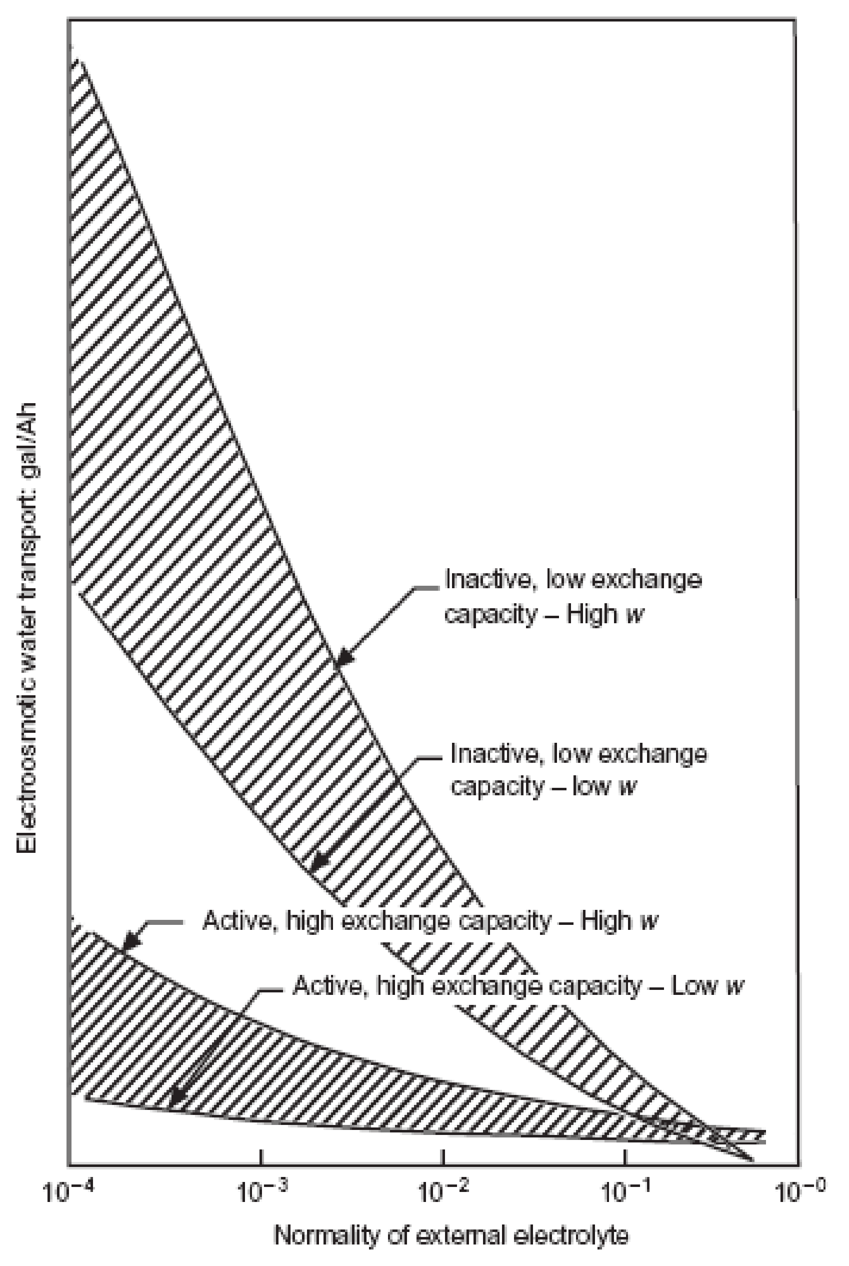
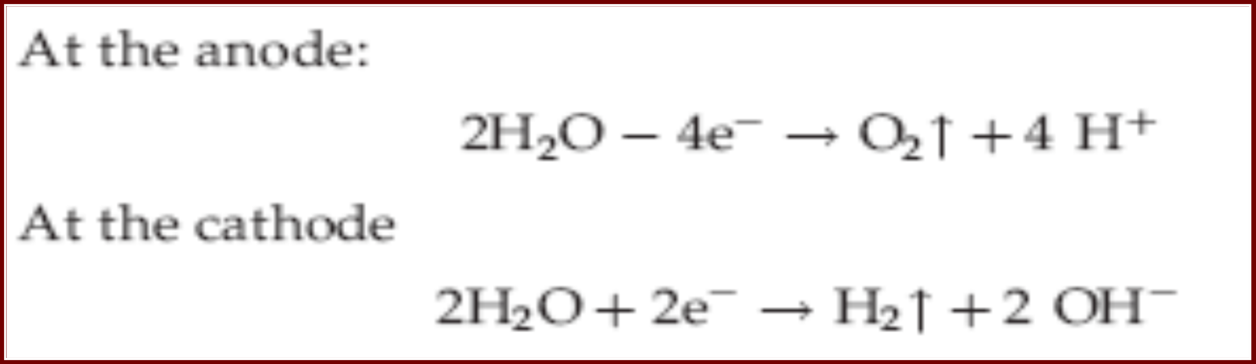


Fig. 2. Schematic prediction of electroosmosis in various clays according to the Donnon concept (after Gray and Mitchell, 1967)

Other Effects of Electrical Application

- The movement of water reduces both the water content and the pore water pressure, hence increasing the effective stress.

- Electrolysis of the pore water at the electrodes causes hydrogen (H^+) and hydroxide (OH^-) ions to be released from the anode and cathode respectively:



At the anode:

$$2H_2O - 4e^- \rightarrow O_2\uparrow + 4\,H^+$$

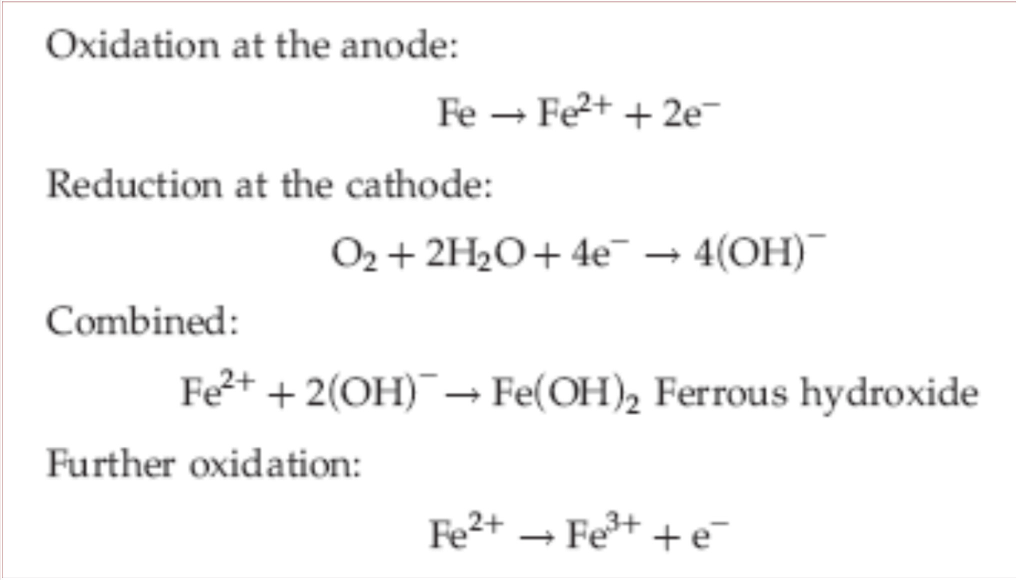
At the cathode

$$2H_2O + 2e^- \rightarrow H_2\uparrow + 2\,OH^-$$

- These ions are drawn towards the opposing electrodes. There are therefore differentials in pH levels across the soil mass. These pH variations in turn change the surface charge on clay minerals, and thus the cation exchange capacity and the solubility of elements within the soil structure.

Electrode Reactions

- The reactions that occur between the electrodes and the pore water depend on the characteristics of the pore water and the material properties of the electrodes.
- Mild steel electrodes were used in some studies. From corrosion theory it is known that oxidation occurs at the anode owing to the loss of electrons, while reduction occurs at the cathode (Owen and Knowles, 1994).



Oxidation at the anode:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^{-}$$

Reduction at the cathode:

$$\mathrm{O}_2 + 2\mathrm{H}_2\mathrm{O} + 4\mathrm{e}^{-} \rightarrow 4(\mathrm{OH})^{-}$$

Combined:

$$\mathrm{Fe}^{2+} + 2(\mathrm{OH})^{-} \rightarrow \mathrm{Fe(OH)}_2 \text{ Ferrous hydroxide}$$

Further oxidation:

$$\mathrm{Fe}^{2+} \rightarrow \mathrm{Fe}^{3+} + \mathrm{e}^{-}$$

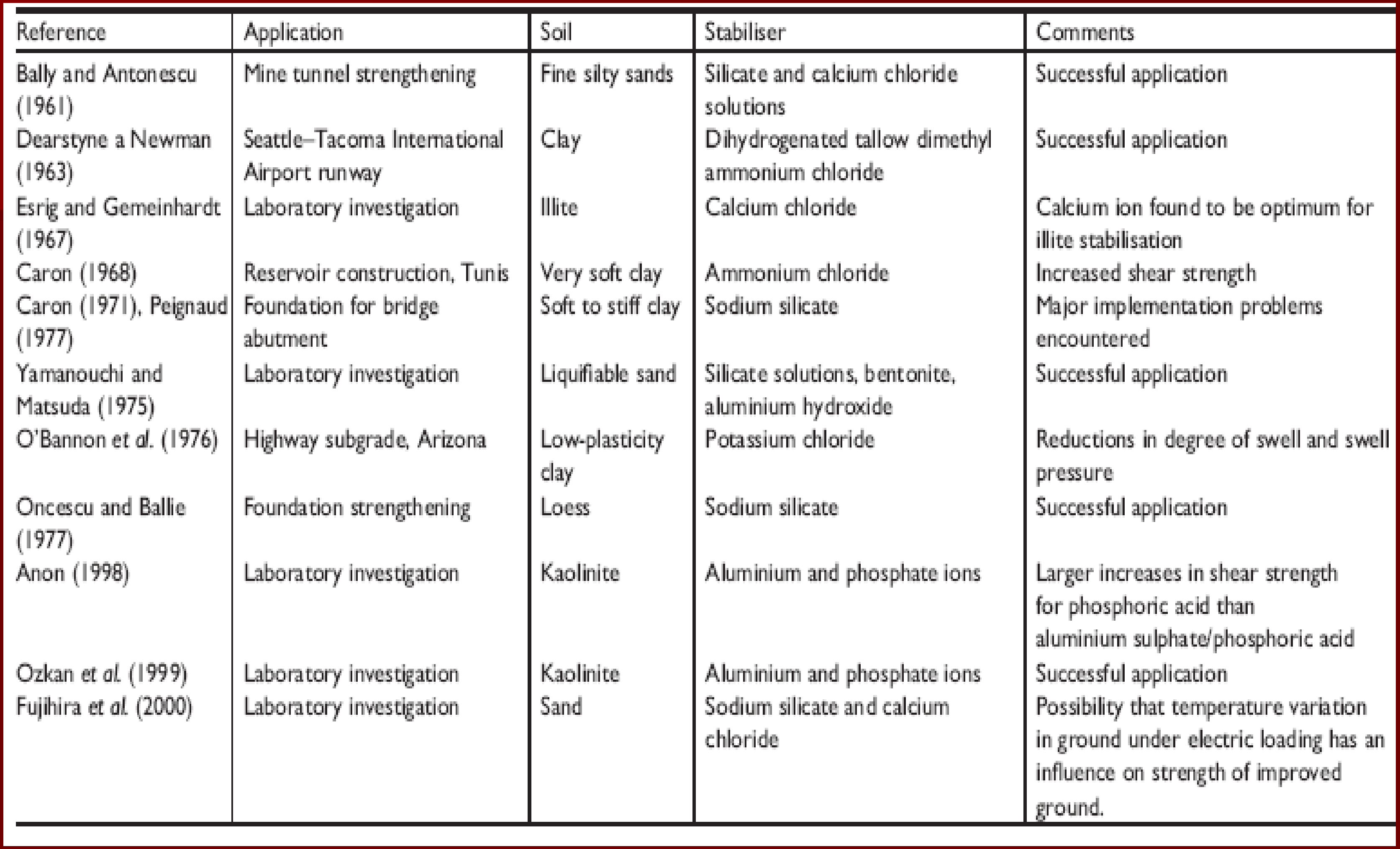
Design Considerations

- Correct electrode installation ensures good electrical contact with the subsurface, while avoiding an electrical bridge through surface water or topsoil (Lo et al., 1991).
- Low electrical resistance can be maintained in the soil by ensuring a high degree of saturation.
- Subsurface features such as slip surfaces, and sand or gravel lenses, may provide electrical bridges where ‘injected’ stabilisers will preferentially migrate.

❑Augered holes may have to be sleeved to prevent infill (i.e. side wall ravelling or collapse), in which case selection of sleeve material requires careful consideration.

❑The effect of any acid/base front propagation through the soil must be considered, particularly in relation to underground services.

❑If treatment is being carried out under existing structures, great care must be taken to control (i.e. avoid significant changes to) the depth of the water table to avoid unwanted ground movement.



Reference	Application	Soil	Stabiliser	Comments
Bally and Antonescu (1961)	Mine tunnel strengthening	Fine silty sands	Silicate and calcium chloride solutions	Successful application
Dearstyne a Newman (1963)	Seattle–Tacoma International Airport runway	Clay	Dihydrogenated tallow dimethyl ammonium chloride	Successful application
Esrig and Gemeinhardt (1967)	Laboratory investigation	Illite	Calcium chloride	Calcium ion found to be optimum for illite stabilisation
Caron (1968)	Reservoir construction, Tunis	Very soft clay	Ammonium chloride	Increased shear strength
Caron (1971), Peignaud (1977)	Foundation for bridge abutment	Soft to stiff clay	Sodium silicate	Major implementation problems encountered
Yamanouchi and Matsuda (1975)	Laboratory investigation	Liquifiable sand	Silicate solutions, bentonite, aluminium hydroxide	Successful application
O'Bannon *et al.* (1976)	Highway subgrade, Arizona	Low-plasticity clay	Potassium chloride	Reductions in degree of swell and swell pressure
Oncescu and Ballie (1977)	Foundation strengthening	Loess	Sodium silicate	Successful application
Anon (1998)	Laboratory investigation	Kaolinite	Aluminium and phosphate ions	Larger increases in shear strength for phosphoric acid than aluminium sulphate/phosphoric acid
Ozkan *et al.* (1999)	Laboratory investigation	Kaolinite	Aluminium and phosphate ions	Successful application
Fujihira *et al.* (2000)	Laboratory investigation	Sand	Sodium silicate and calcium chloride	Possibility that temperature variation in ground under electric loading has an influence on strength of improved ground.

Table 1. Various reported research and case studies relating to electrokinetic stabilisation

Electrokinetic Stabilisation - Chief Mechanism

- From studies of clay mineralogy it is known that clays are made up of small particles (<0.002 mm) with a very large surface area in comparison to their mass.

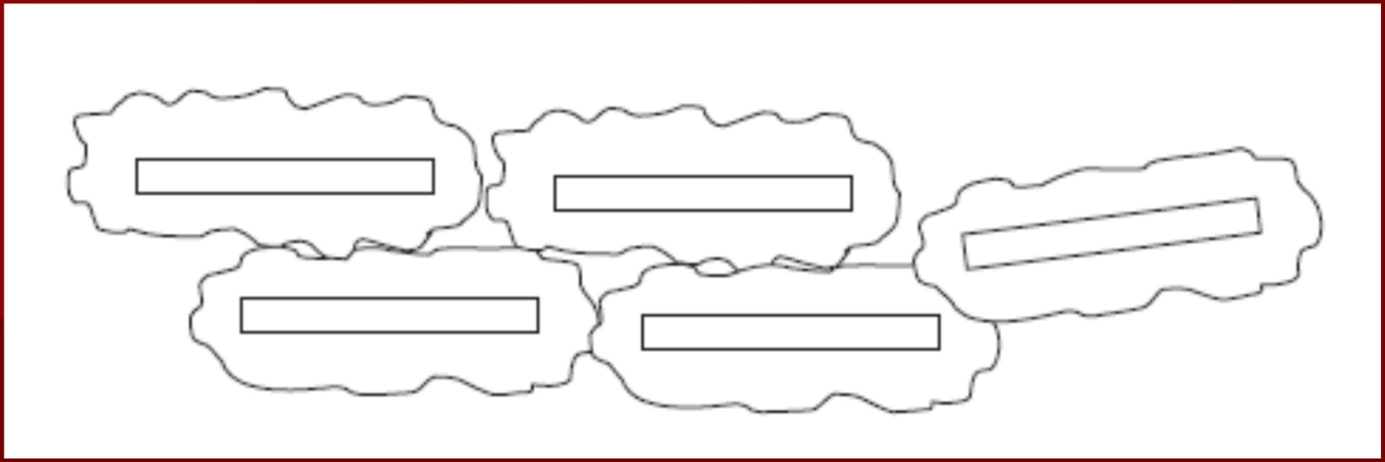
- The properties of a clay are therefore greatly influenced by the surface forces. These surfaces are negatively charged, primarily as a result of the isomorphous substitution of aluminium or silicon atoms by lower-valency atoms.
- This negative charge attracts (dipolar) water molecules, resulting in the clay particles being surrounded by layers of water, known as diffuse water layers (or diffuse double layers). The concentration of cations available in the pore water and the surface charge of the clay particle together control the thickness of this layer.

- In addition, the pH of the system can influence the negative charge of the clay particles, in some cases (e.g. kaolinite) significantly, and therefore directly influence the thickness of the diffuse water layer.

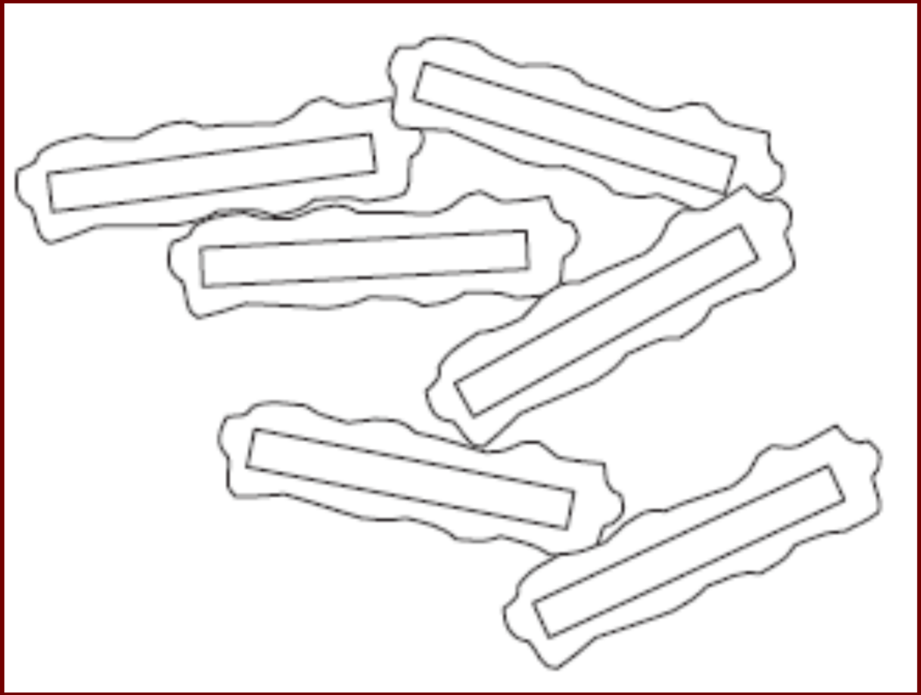
- The cations commonly found in the diffuse water layer and the pore water are variously sodium, potassium, calcium, magnesium and lithium, and in some cases higher order ions are also present (Little, 1987).

- When cations of a higher valency and/or a larger ionic radius, such as calcium, silicon or aluminium, are introduced in significant concentrations, they saturate the solution and become adsorbed at the clay surface in preference to those ions originally present.

- The result of this cation exchange, due for example to the classic case of lime (and hence calcium ion) addition, is a considerable reduction in the thickness of the diffused water layer, as illustrated in Fig. 3.
- This allows closer contact between the clay platelets, which promotes edge-to-face attraction, or flocculation, and results in changes in the soil’s workability, permeability, plasticity and swell properties.
- Alteration of the soil pH results in changes in the solubility of the clay minerals present.
- The reaction products such as amorphous calcium aluminate hydrate and calcium silicate hydrate gels, crystallises with time to form a strong, brittle solid. This process is termed stabilisation.



a.



b.

Fig. 3. Flocculation of clay platelets (after Little, 1987)

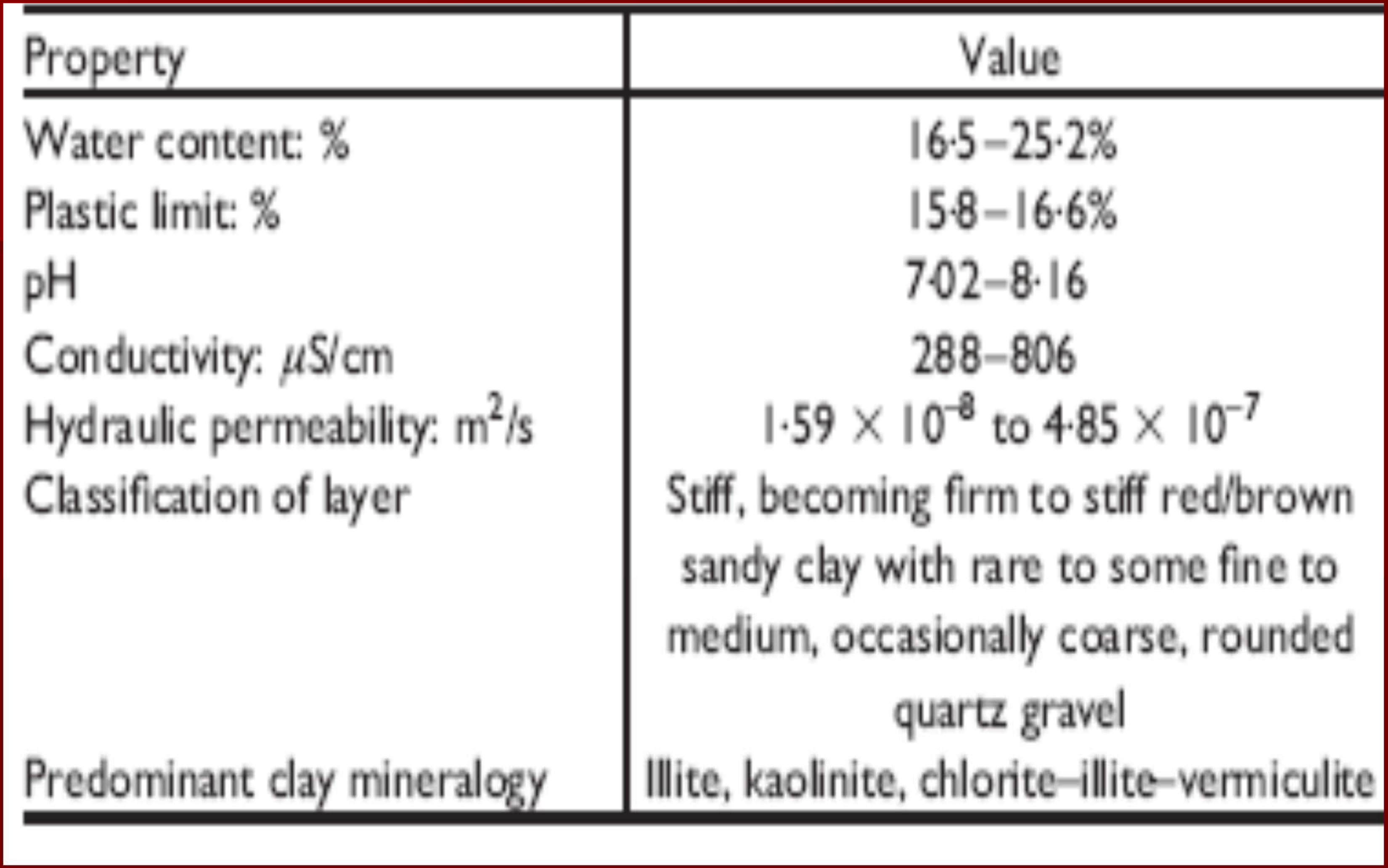
(a) Parallel arrangement of clay particles with hydrated water layers.

(b) Edge-to-face attraction induced by thin water layer, which allows attractive forces to Dominate.

Case Studies

Ground Conditions

- A field trial was carried out near Holywell, North Wales, UK in an area which experienced some landslip.
- The trial site was located within this area on a flat bench some 10–15 m from any recent landslip.
- Initial ground investigations revealed the site to consist of 0.1 m of made up ground, overlying 1.3 m of glacial clay (properties detailed in Table 2), with a sand lens beneath this layer.
- Groundwater was not encountered within 1.1 m of ground level.



Property	Value
Water content: %	16·5–25·2%
Plastic limit: %	15·8–16·6%
pH	7·02–8·16
Conductivity: μS/cm	288–806
Hydraulic permeability: m^2/s	$1{\cdot}59 \times 10^{-8}$ to $4{\cdot}85 \times 10^{-7}$
Classification of layer	Stiff, becoming firm to stiff red/brown sandy clay with rare to some fine to medium, occasionally coarse, rounded quartz gravel
Predominant clay mineralogy	Illite, kaolinite, chlorite–illite–vermiculite

Table 2. Material properties of glacial clay

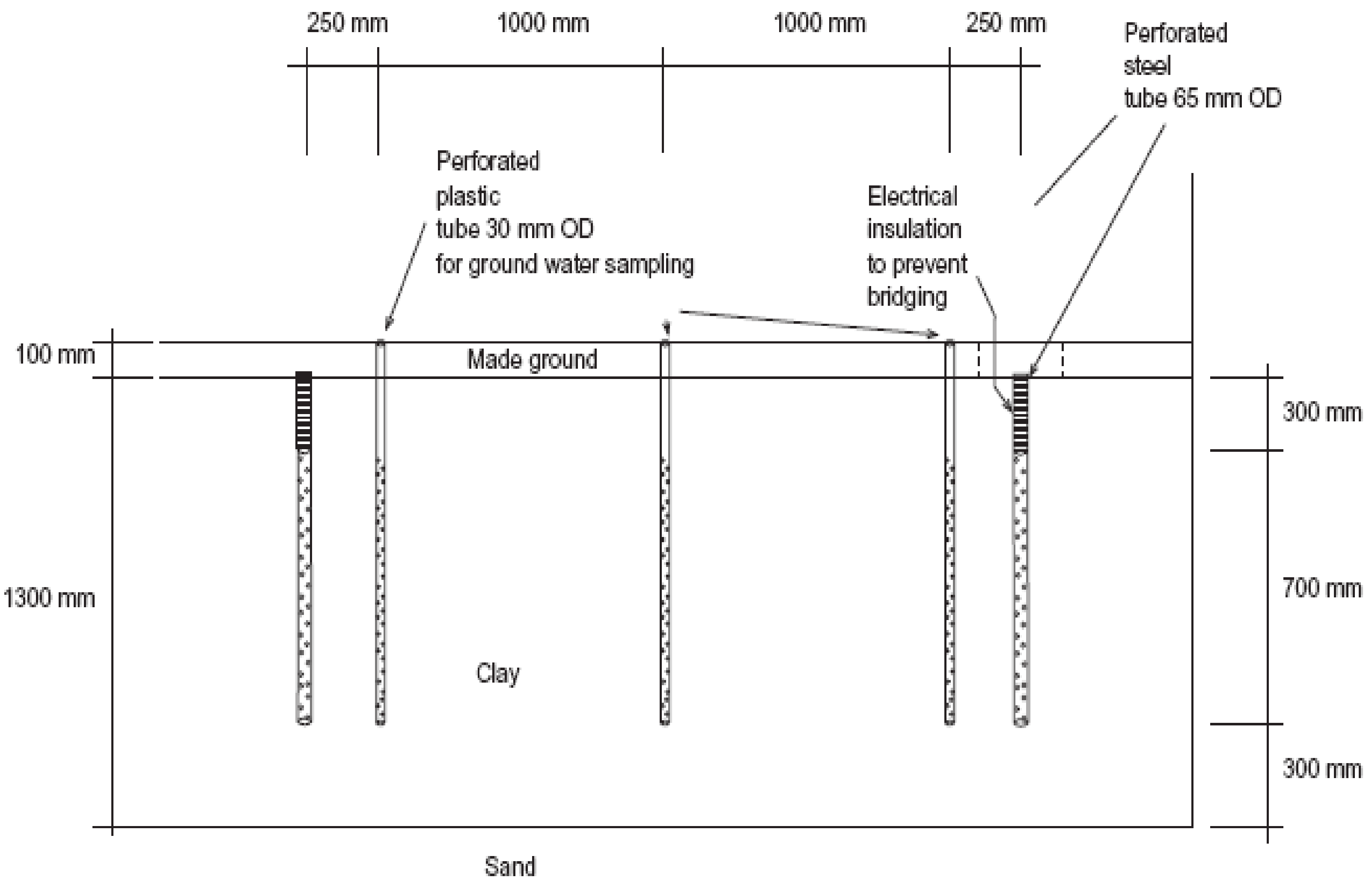


Fig. 4. Elevation of electrodes and sampling tubes

Field Trial Installation and Electrical Regime

- After vegetation stripping, electrodes and sample tubes were installed, as in the layout detailed in Fig. 4, in 65 mm diameter holes augered to a depth of 1.1 m within the glacial clay, which, with the perched water table so close to the surface, was fully saturated.

- The electrodes used were mild steel tubes 1 m long, 65 mm (external) diameter and 2.4 mm thick. These steel tubes were crimped to a point at one end to aid installation.

- The top 300 mm was insulated with insulation tape to prevent electrical bridging occurring through the topsoil.

- To allow the solution to flow into the soil, 104 holes (25 mm in diameter) were drilled at 50 mm centres in the region 300 mm from the top to 150 mm from the bottom of the tube. The electrodes were pushed into the holes, which had the same nominal diameter, and a snug fit was therefore ensured.
- In addition, electrical continuity was provided by the fluids fed to the electrodes.
- The sample tubes were perforated plastic tubes 30 mm in diameter.

•In order to assess the effect of electrical current application, a control arrangement was installed parallel with and 7 m away from the main test arrangement, and repeated intermediate sampling between arrangements was carried out to ensure that there was no cross-contamination.

•The electrodes were connected in a circuit that passed a constant direct current between the electrodes through the soil.

•To examine the effect of different levels of driving force on the migration rates achieved, the potential difference was initially set at 8 V for 0–4 days and was thereafter raised to 20 V for 4–12 days and 50 V for 12–27 days.

Chemical Addition

- The chemical solution was fed to the electrodes by means of a tube from a 210 litre tank.

- The level of chemical solution, within the electrode, was maintained at 300 mm below ground level by means of a buoyant tube connected to a float valve (Fig. 5).

- Calcium chloride ($CaCl_2$) solution (186 g/l) was applied through the anode for the full 27-day duration of the trial.

- Sodium silicate (Na_2SiO_3) solution (120 g/l) was applied through the cathode for the period 0–17 days, the point of chemical addition changing to midway between the electrodes (via a perforated steel tube, which replaced the central plastic sampling tube) for the period 17–27 days owing to the lack of flow of this stabilising solution into the ground.

Monitoring

- Monitoring was carried out every 2–4 days, including measurement of the location of the temporary (perched) water table and the solution levels within storage tanks.
- Samples of groundwater were taken from the sample tubes, and pH and conductivity were assessed.
- Samples of soil were taken from various locations at depths 0–0.25, 0.25–0.50, 0.50–0.75 and 0.75–1.00 m using a 20 mm diameter hand auger after 0, 16 and 27 days with the following tests performed: water content, pH, conductivity and (where sufficient material allowed) plastic limit.
- Determination of water content, plastic limit and conductivity was carried out as per standard procedures.

Results

Effect of Chemical Addition

- The effect of the applied electric current on the rate of chemical addition through the steel tubes is illustrated in Fig. 6.

- It is clear that the amount of chemical solution ($CaCl_2$) flowing through the anode is significantly greater than where no current is applied, whereas the applied current had, apparently, relatively little effect on the amount of Na_2SiO_3 drawn into the soil (i.e. flowing through the cathode for 0–17 days and for 17–27 days through the central sampling tube). However, closer scrutiny of these data indicates that the flow is diminished by the current over the first 17 days.

This was attributed to the inhibition to migration of an inward flow of water to the cathode when a current is applied, whereas in the control section migration is not inhibited in this way. This in itself was an interesting finding.

A marked increase in chemical addition into the soil when the sodium silicate solution was added centrally proves this point, as there would be no tendency for water to flow inwards, but in this case the tendency would be for the water to flow past the injection point to the cathode, thus drawing the solution with it.

Further, assuming that the flow of chemical is due solely to hydraulically and electrically induced flows (and ignoring second-order coupling effects; Mitchell, 1991), the effect of the applied electrical current, for days 4–12, was quantified.

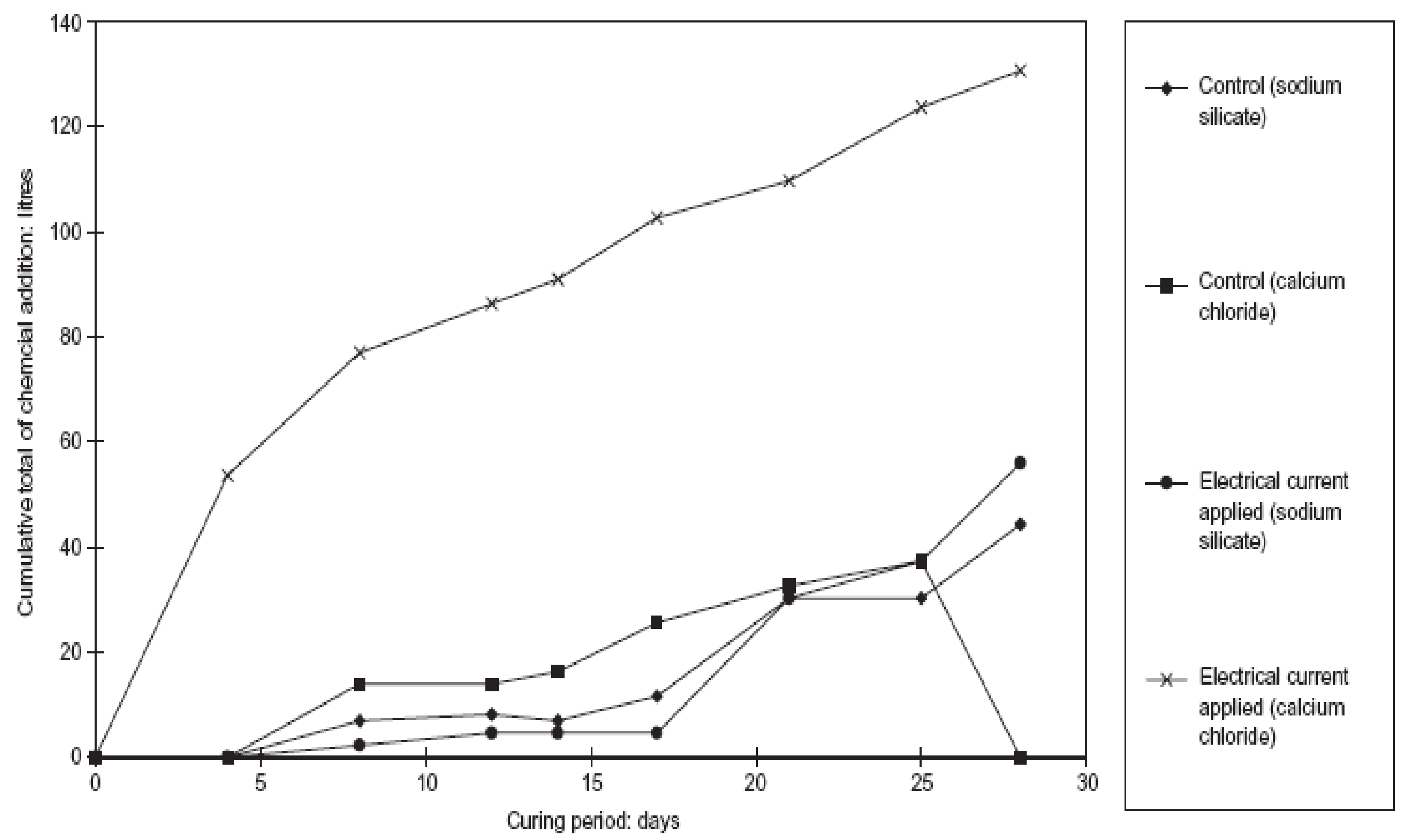


Fig. 6. Cumulative flow of chemical solution through anode (0–27 days), cathode (0–17 days) and central steel tube (17–27 days)

Position of Water Table

- Figure 7 illustrates the effect of the hydraulic gradient and electrical current on the position of the phreatic surface.

- The effect of maintaining the level of chemical solution within the steel tubes to 300 mm below the ground level is illustrated by a raising of the phreatic surface within a distance of approximately 0.7–1.0 m from the steel tubes in the control section.

- The effect of the electrical current is evident within the region that lies up to 1.1 m from the cathode, where the phreatic surface (and thus the pore water potential, and hence the pore water pressure) is raised by up to 500 mm in comparison with the control arrangement.

From examination of Fig. 6 it is evident that there is little flow of chemical solution from the cathode, whereas much greater flow is observed through the anode. It is thus evident that the heightened phreatic surface is due to the migration of pore fluid from the anode to the cathode, and indeed it is this effect that is limiting the outward flow of sodium silicate solution from the cathode when a current is applied.

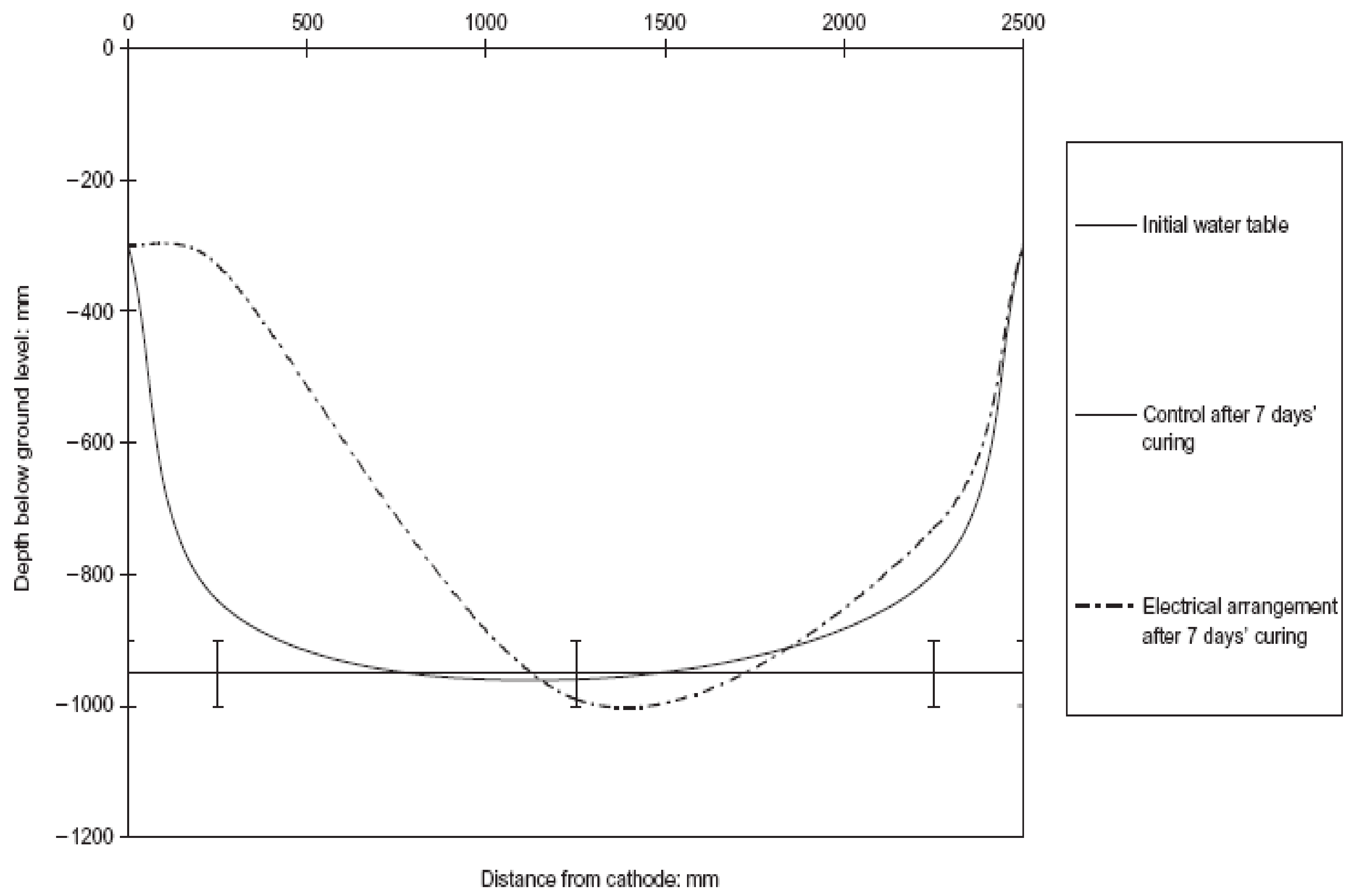


Fig. 7. Depth of temporary water table after 7 days

pH

- The pH was found to reduce up to 2 m from the anode, whereas small increases in pH were observed within approximately 0.7 m of cathode (Fig. 8).

- The initial values of pH were found to decrease with depth (pH = 7.80 at 0 – 0.5 m bgl and pH = 7.49 at 0.5–1.1 m bgl). The increases observed may be attributed to the reduction of water (due to electrolysis reactions occurring in the region close to the cathode, whereas the decreases observed may be attributed to electrode corrosion and the oxidation of water occurring at and around the anode.

It is also clear that these effects reduce with depth. (Sampling from depths below the water table was not possible: hence the limited dataset in Fig. 8 below 0.5 m.)

From examination of Fig. 8 it would appear that there is a much greater production of hydrogen ions than of hydroxide ions. Fig. 9. Molar concentration of hydrogen and hydroxide ions with distance from cathode

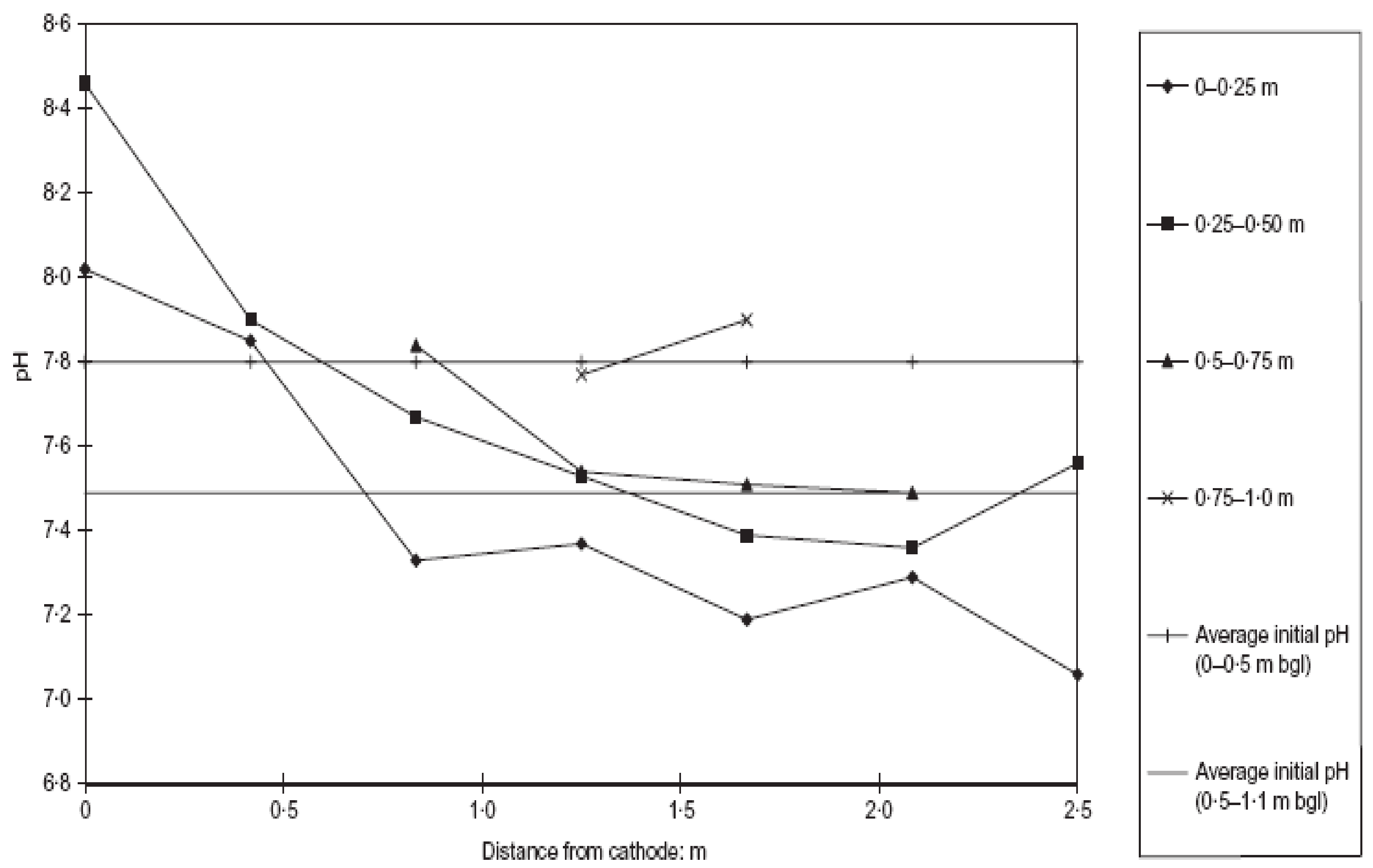


Fig. 8. Variation of pH with distance from cathode for various depths after 27 days

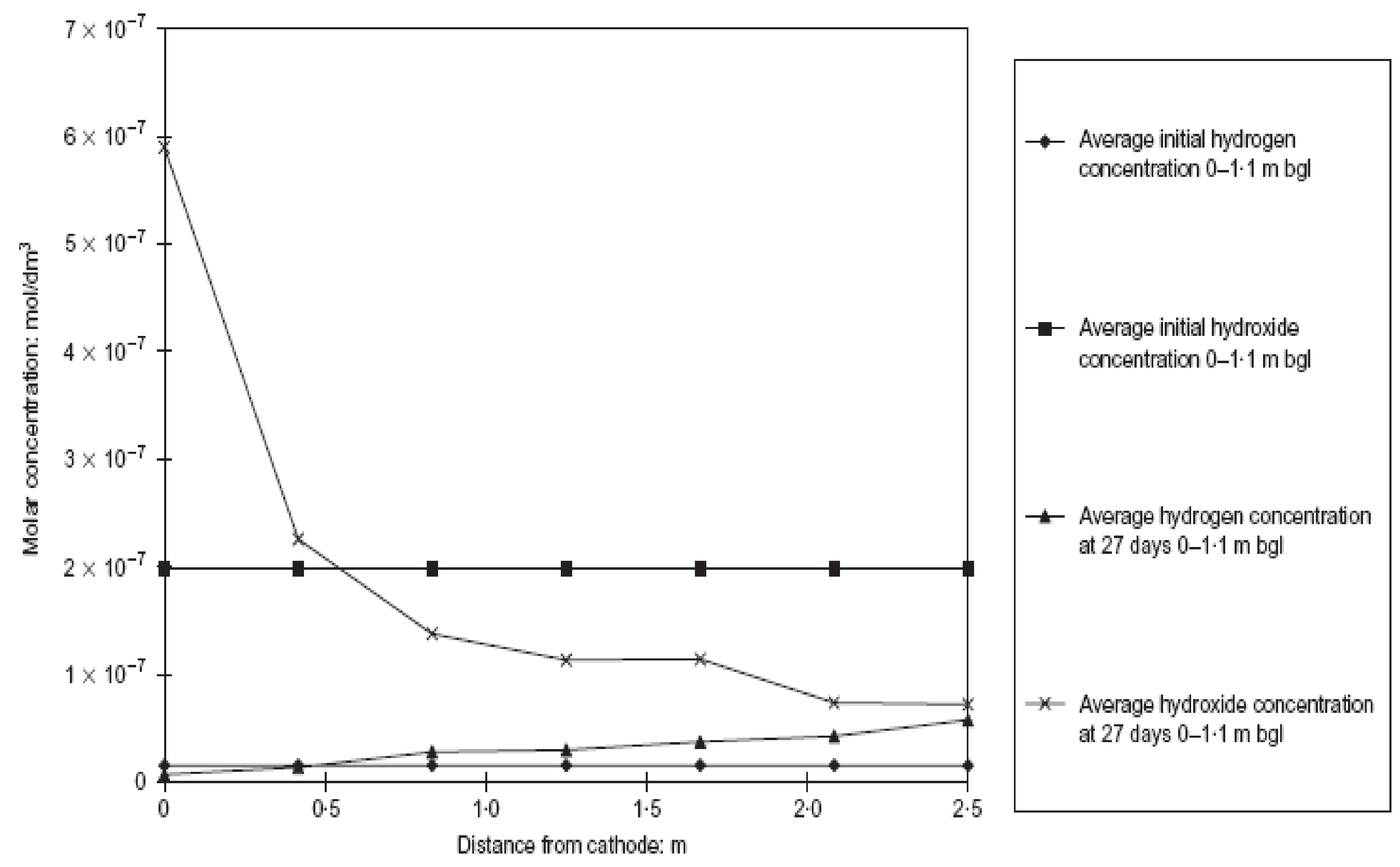


Fig. 9. Molar concentration of hydrogen and hydroxide ions with distance from cathode

Conductivity

- It is evident from Fig. 10 that there is a general decrease in soil conductivity as a result of electrical current application.

- However, conductivities of 4560 and 8130 micro S/cm (i.e. values far off the scale of the graph) were observed at depths of 0–0.25 m and 0.25–0.50 m below ground level respectively in the regions around the anode after 27 days.

- This may be attributed to the increased concentration of calcium chloride solution within the pore fluid around this region, and the presence of Fe^{2+} and/or Fe^{3+} ions resulting from corrosion of the anode.

The conductivity of a solution is governed by the movement of ions within a solution. The factors affecting solution conductivity include:

- ❖The nature and concentration of solutes
- ❖The quantity of ions within the solution
- ❖The charge of each ion within solution
- ❖The freedom of ionic movement within solution
- ❖The solution temperature.

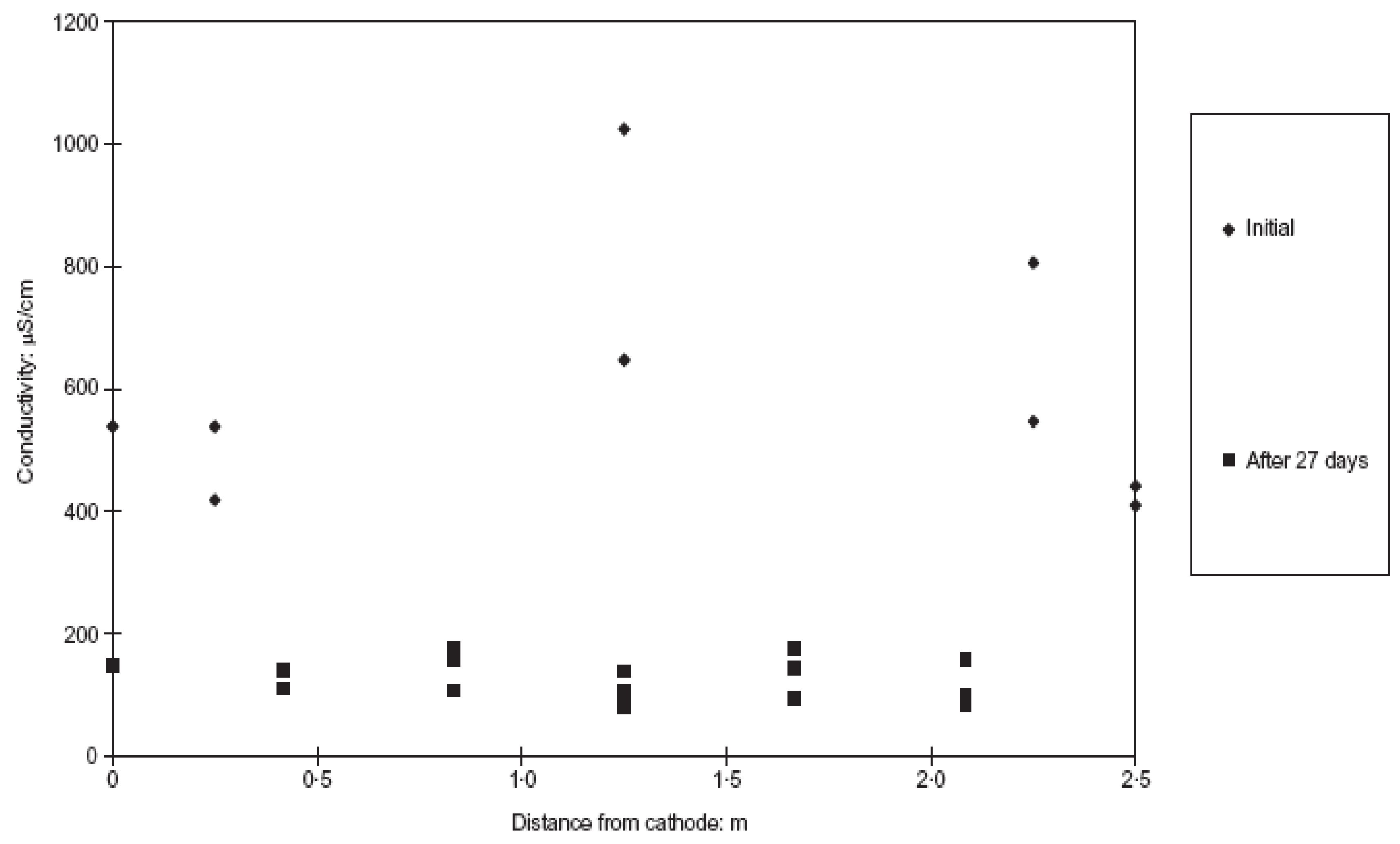


Fig. 10. Conductivity with distance from cathode at various depths

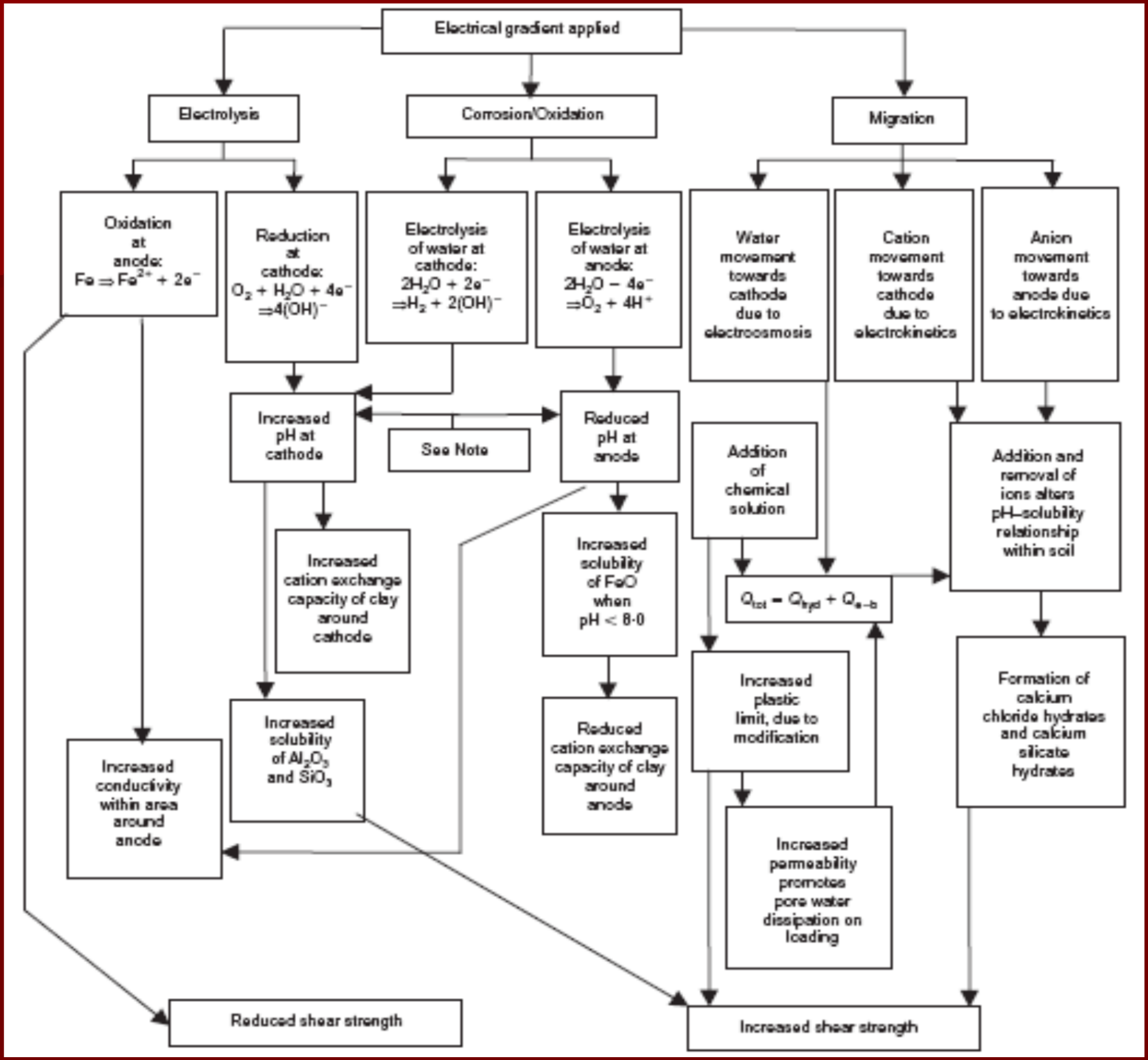


Fig. 11. Flowchart illustrating the various processes involved in electrokinetic injection.

Note: Over the range of pH considered, a large increase in hydroxide ion concentration leads to a small increase in pH, whereas a small reduction in hydrogen ions leads to a large decrease in pH

Conclusions

- The application of an electrical current caused pore water to flow from the anode to the cathode, as expected, and thereby to raise significantly the pore water pressure in the zone around the cathode extending almost halfway between the electrodes.

- The flow of pore water due to the application of an electrical current was approximately five times greater than the flow of pore water due to the application of a hydraulic gradient (by maintaining the fluid level 0.9 m above the water table as a result of filling the steel tubes with chemical solution).

- The flow of water was sufficiently strong to inhibit, almost totally, the migration of silicate ions from the cathode towards the anode.

- The study allowed hydraulic and electroosmotic flows to be calculated, and therefore the electroosmotic conductivity to be deduced. The electroosmotic conductivity of the glacial till was 1.3–2.5 x 10^{-9} m^2/Vs.

- The pH was found to increase in the region close to the cathode and decrease in the region close to the anode, owing to the electrolysis of pore water and oxidation/reduction reactions.

- The migration of hydrogen ions from the anode was more widespread than that of hydroxide ions from the cathode, because of both the presence of groundwater flow and the greater effect of the raised H^+ ion concentration relative to the OH^- ion concentration. This meant that the acid front extended further and caused a general depression in the pH levels across the test section until the cathode was approached, where upon the pH levels rose significantly above the original baseline reading

- The conductivity data show only a general trend of ion concentration changes, but in the trial sections there was a considerable reduction in conductivity over almost the whole length, the exception being close to the anode, where very high levels of conductivity were recorded.

- Calcium chloride was found to migrate at least 750 mm after 16 days when electric current was applied. This was attributed to the electroosmotic flow counteracting the tendency of chloride ions to remain at the anode.

- The formation of calcium silicate hydrate was detected after 27 days. This was attributed to the reactions resulting from the mixing of calcium ions transported from the anode and silicate ions from the central injection point.

  - To achieve this effect in future trials, it is apparent that the silicate solution would need to be injected closer between the anode and the section requiring stabilisation.

- The plastic limit data were limited, owing to sampling restrictions, and were shown to be complex to interpret.

- Barker et. al. (2004)
- Ground Improvement, 8,No.2, 47 -58

Why Eletrokinetic Geosynthetic(EKG) ?

- Electrokinetic geosynthetic (EKG) materials retrofitted to belt filter presses have increased the solids contents of sewage cake from ~20% dry solids to ~31% dry solids and diamond mine tailings from ~62% dry solids to ~75 dry solids%.
- The former resulted in a 40% volume reduction and prospective cost savings to water companies of £132,000 per belt filter press machine per annum.
- The latter offered the possibility of substantial cost savings to mining companies associated with tailings disposal and management.

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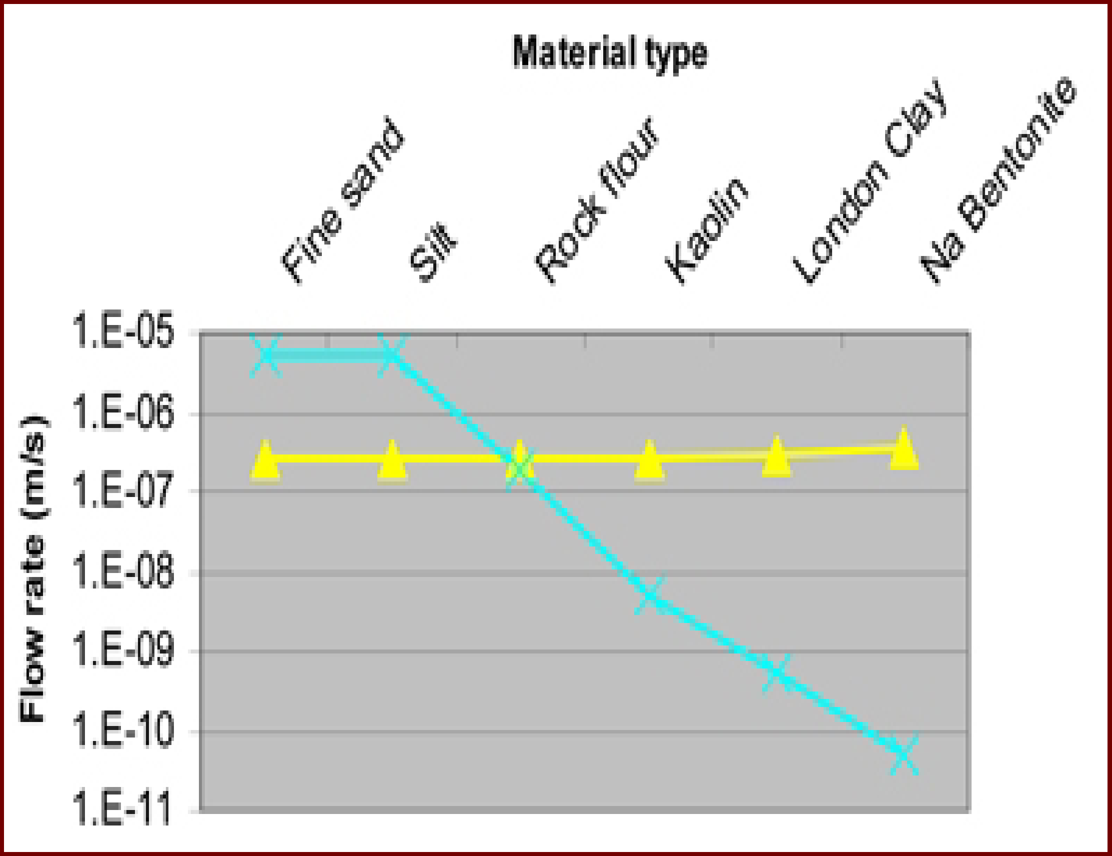
EKG materials have applications in ground dewatering including:

- Electrokinetic belt filter press
- Electrokinetic plate filter press
- EKG dewatering bags for mixed wastes
- In situ dewatering of lagoon wastes

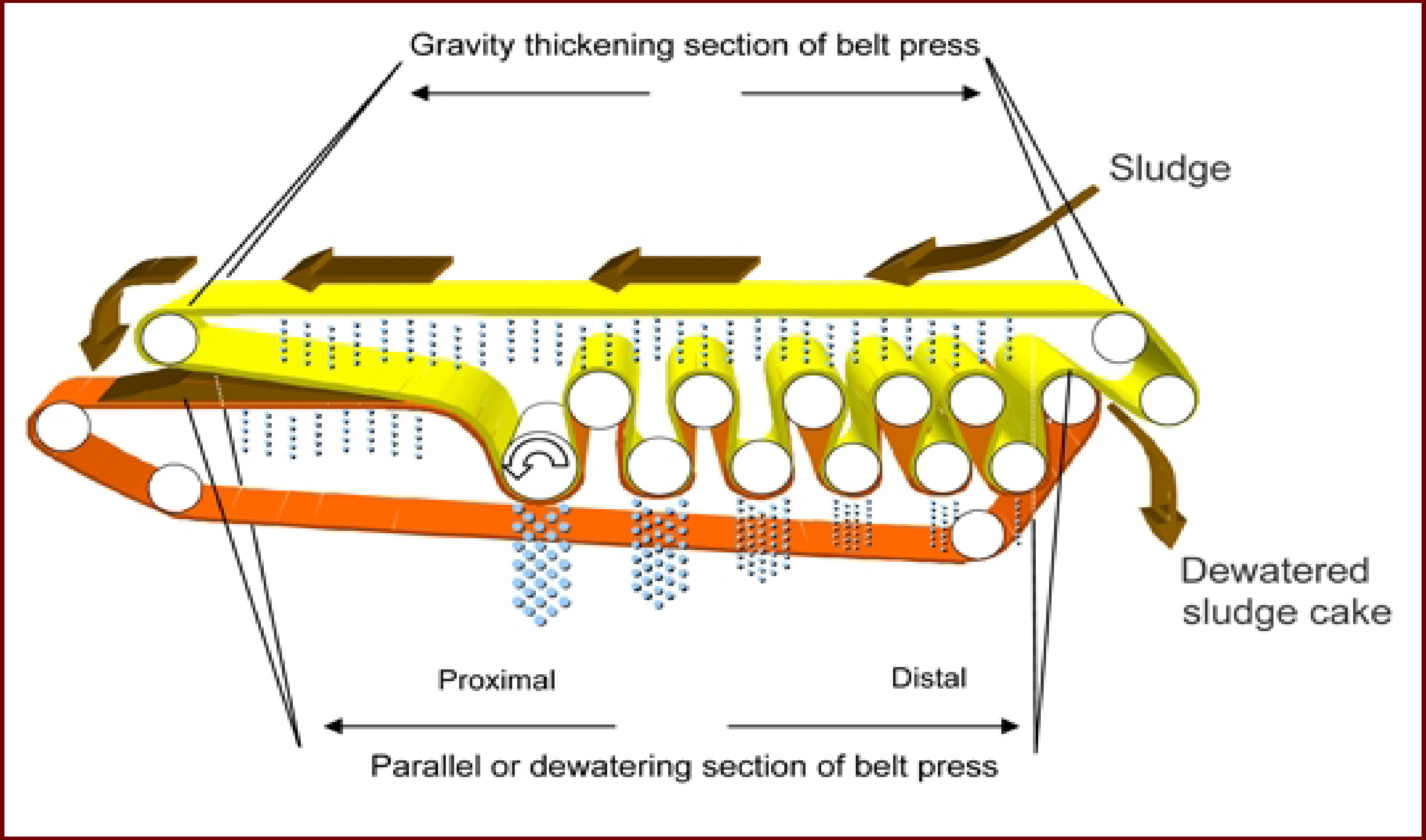
Dewatering of materials using filtration or centrifugation becomes increasingly difficult as the materials become progressively more fine grained. Electroosmosis can aid the dewatering process and is particularly suited to fine grained materials.

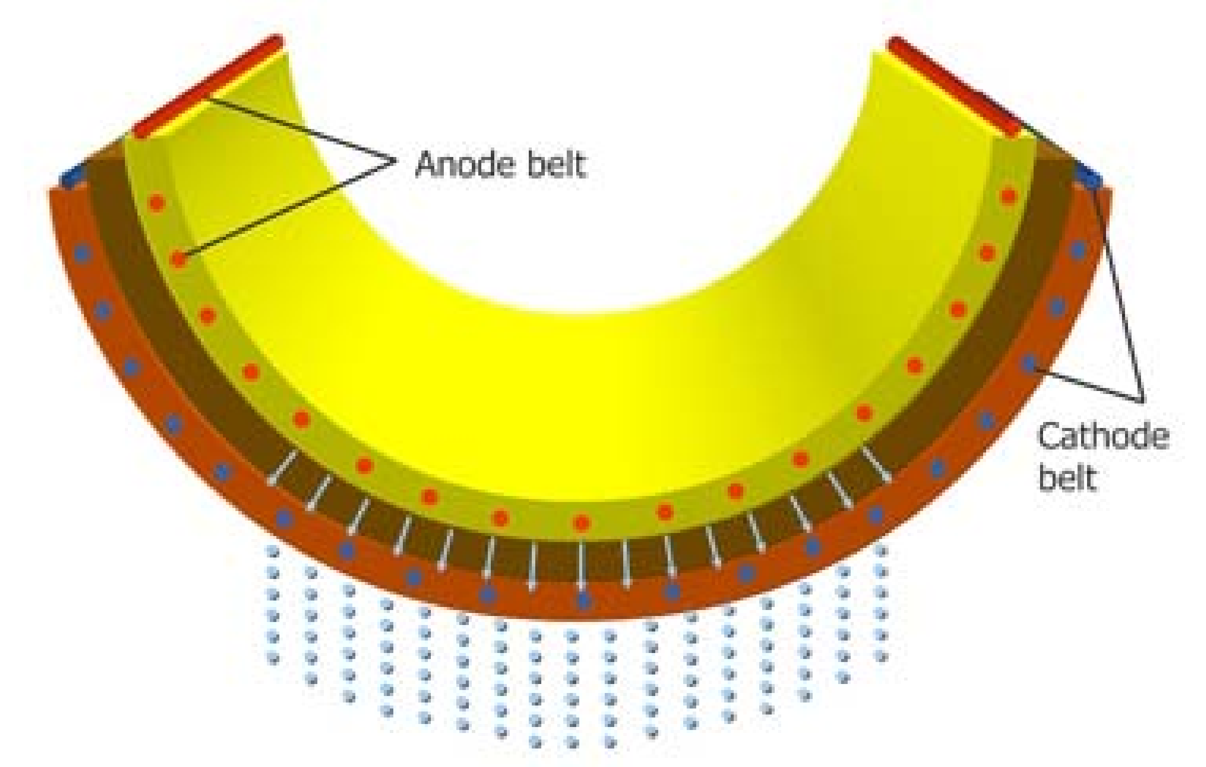
The benefits of this are particularly evident in materials such as clays, sludges and fine tailings, see graph below.



Eletrokinetic Belt filter press:

Electrokinetic belt filter press technology has been developed by Electrokinetic Ltd. The basic set up is shown below.




Anode belt
Cathode belt

Basic concept of EKG

The fundamental concept of the system is to add the electrokinetic effects whilst preserving, the existing hydraulic dewatering performance. The system operates by confining the voltage to and controlling the voltage within the dewatering zone. It is designed to be adaptable to a wide range of existing conventional belt filter presses.The benefits of the electrokinetic belt filter press over alternative dewatering methods include:

Increased solids content of dewatered cake, e.g. raising dewatered sewage cake from 20% dry solids to over 30% dry solids

- Improved stackability of dewatered cake
- Reduced overall energy consumption

Case studies

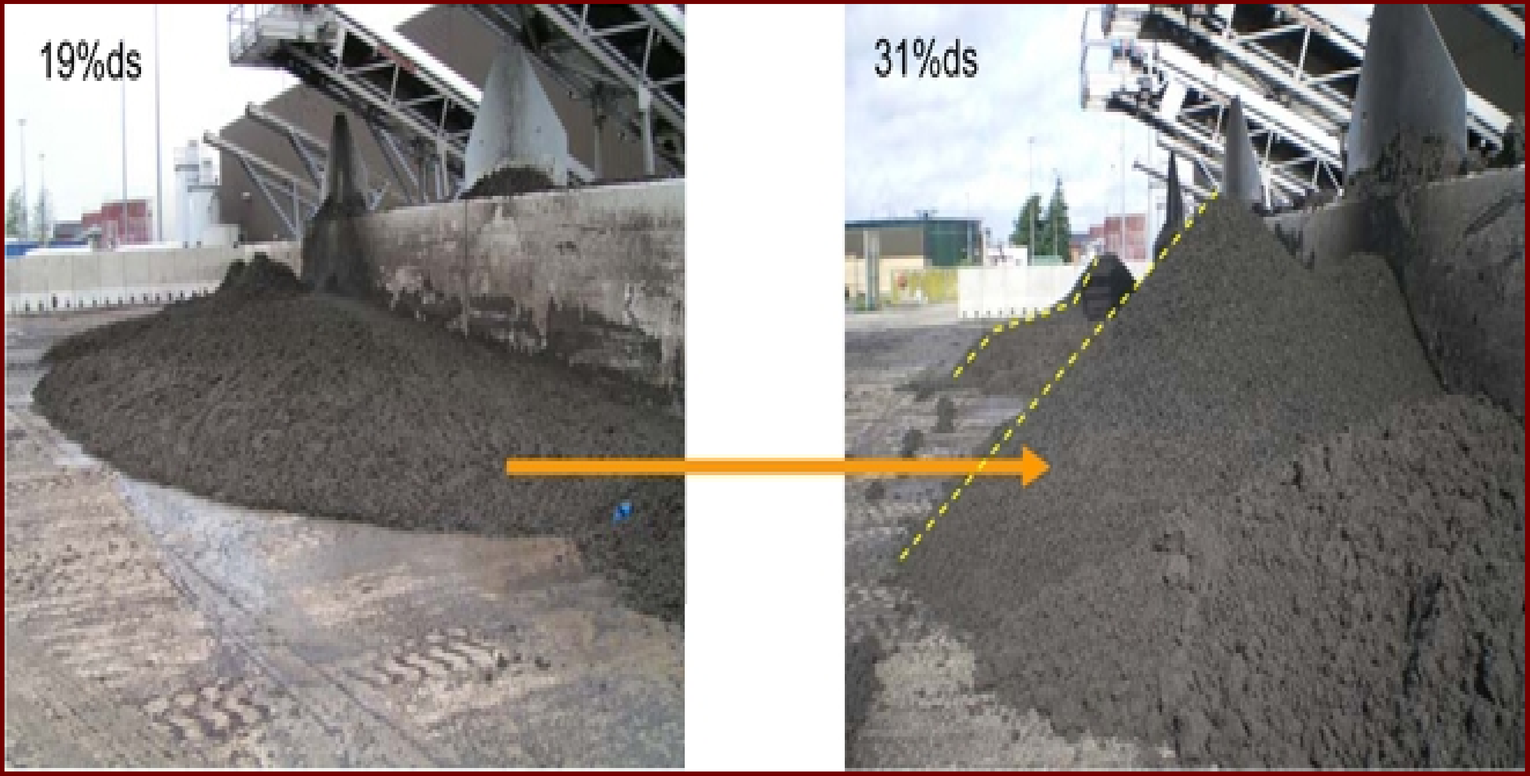
1. **Dewatering of sewage sludge :**

- Treatment of raw sewage produces sludge with solids content in the range 1-3%. The requirement to dewater and re-use or dispose of these materials is a fundamental issue and persistent and complex problem for all water companies in any country.
- Conventional dewatering of sewage sludge involves the use of belt filter presses or centrifuges to reduce the water content to permit disposal.

Continued…

- Disposal is best effected if the sludge material has a dry solids content greater than 25-30%. In general terms conventional belt press treatment systems produce a sludge cake with a dry solids contents significantly below this level.
- A step change in belt press dewatering performance has been achieved by combining conventional belt press technology with EKG. This breakthrough adds the dewatering effect of electroosmosis to that of conventional hydraulic dewatering.
- The form of the EKG is an Electrokinetic patented enhancement of standard filtration belts.

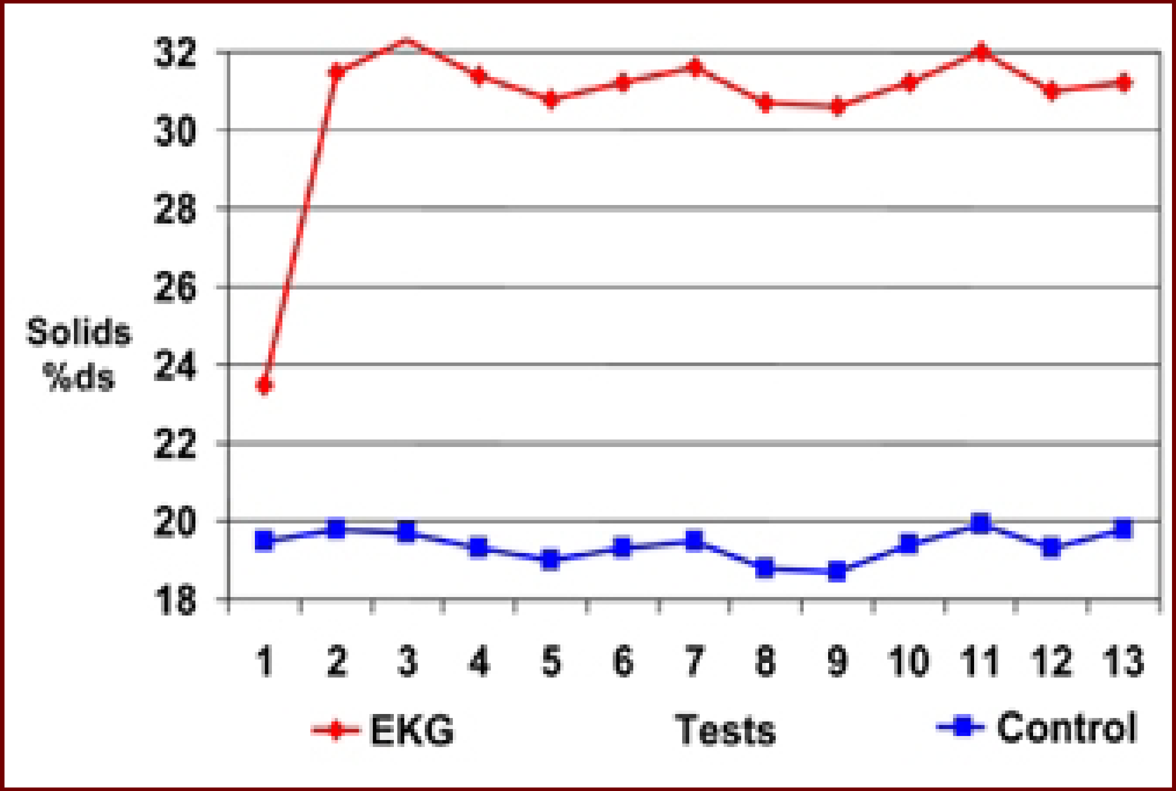
An example of using EKG technology in sewage dewatering by Thames Water Company (London) is shown below.



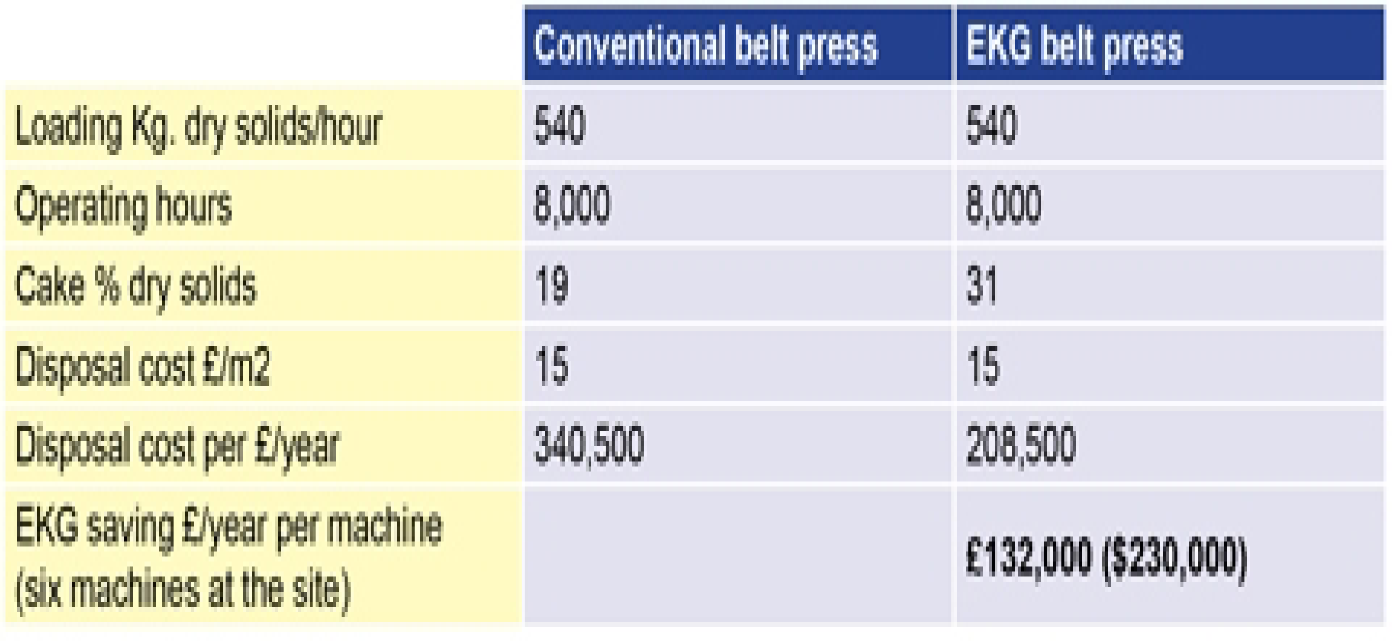
Left: Conventional treatment, 19% dry solids content. Right: EKG enhanced treatment - 31% dry solids yielding 39% volume reduction and improved stacking

- This shows that, at a dry solids content of 19%, the material is still in a semi-liquid form and difficult to transport, this can require mixing with straw to provide mechanical stability. If disposal is by incineration then fuel oil has to be added to increase the thermal content of the sludge.
- At the 31% dry solids content produced by the EKG treatment, the sludge is now a solid and can be handled without the addition of bulking material and that the volume of material to be disposed of is reduced by 39%.

In addition, at 30+% dry solids many sludge cakes are auto-thermic and can be used as a fuel.



The economics and cost savings of using EKG technology to dewater sewage sludge has been identified by McLoughlin (2005) as tabulated below.



	Conventional belt press	EKG belt press
Loading Kg. dry solids/hour	540	540
Operating hours	8,000	8,000
Cake % dry solids	19	31
Disposal cost £/m2	15	15
Disposal cost per £/year	340,500	208,500
EKG saving £/year per machine (six machines at the site)		£132,000 ($230,000)

Disposal cost comparison (after McLoughlin 2005)

Based on typical sewage treatment site with six dewatering machines, this will give a potential cost saving of c£800,000 per annum.

Case study: Ground Engineering

2.Electrokinetic stabilisation of a railway embankment

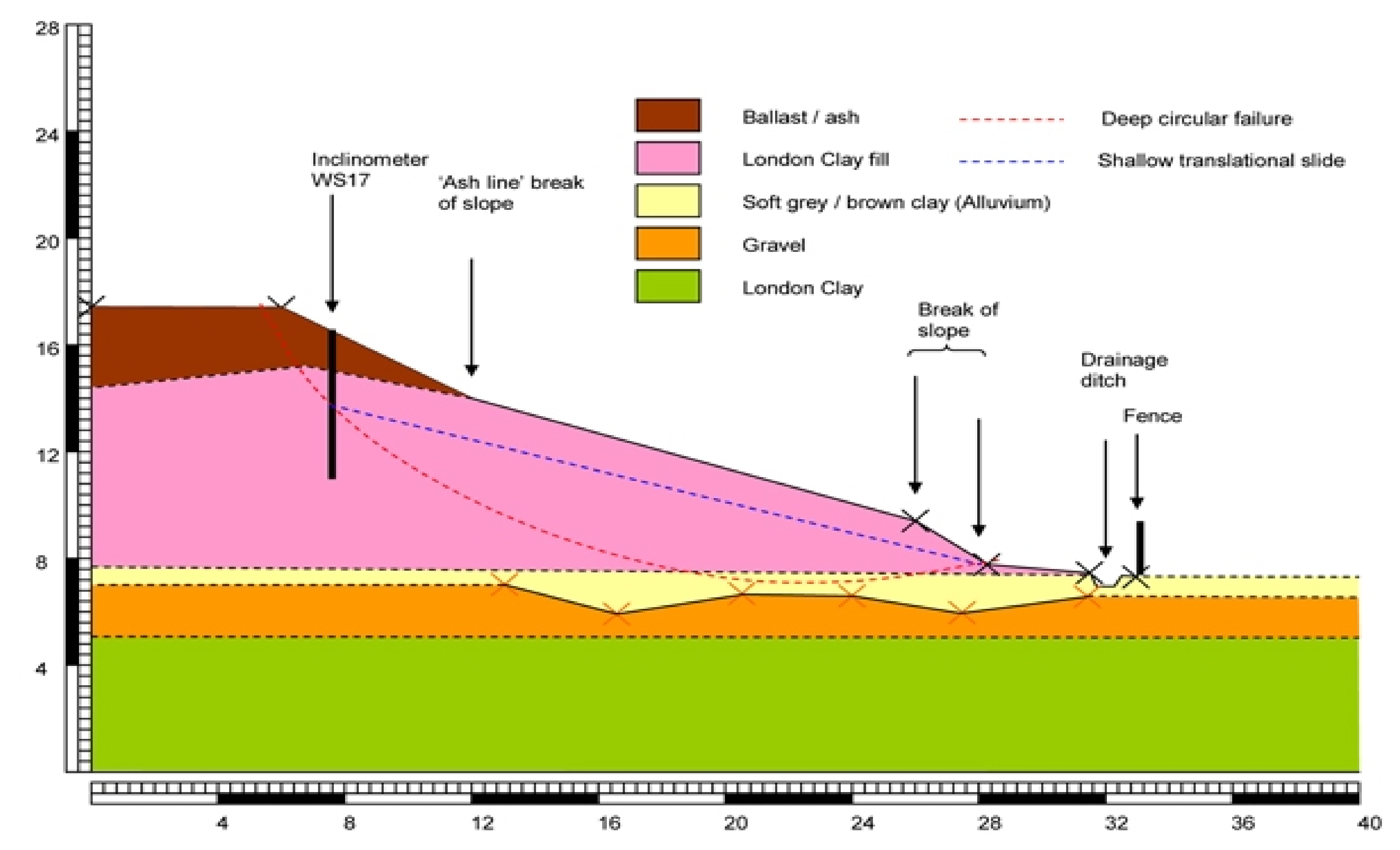
Electrokinetic geosynthetic (EKG) technology has been used to successfully stabilise a failing clay embankment in London resulting in a 26% cost reduction and a 47% reduction in carbon footprint over conventional methods.

Network Rail identified EKG ground treatment as a novel slope treatment method which could:

- Stabilise the slope
- Requires only modest access owing to the absence large plant
- Involves low relative energy consumption
- Reduce cost

A trial was conducted on a 22m stretch of a 9m high Victorian embankment. The embankment had been constructed by end tipping a mixture of weathered London Clay and other material such as brick and stone fragments onto underlying alluvium and terrace gravels. An assessment of the embankment identified several sections as unstable.

Inclinometer readings indicated a slip surface at approximately 2.5m depth, which could either be a shallow translational slide or a deeper circular failure. Stability calculations indicated a factor of safety (FoS) for the slope of only 1.0.



EKG treatment:

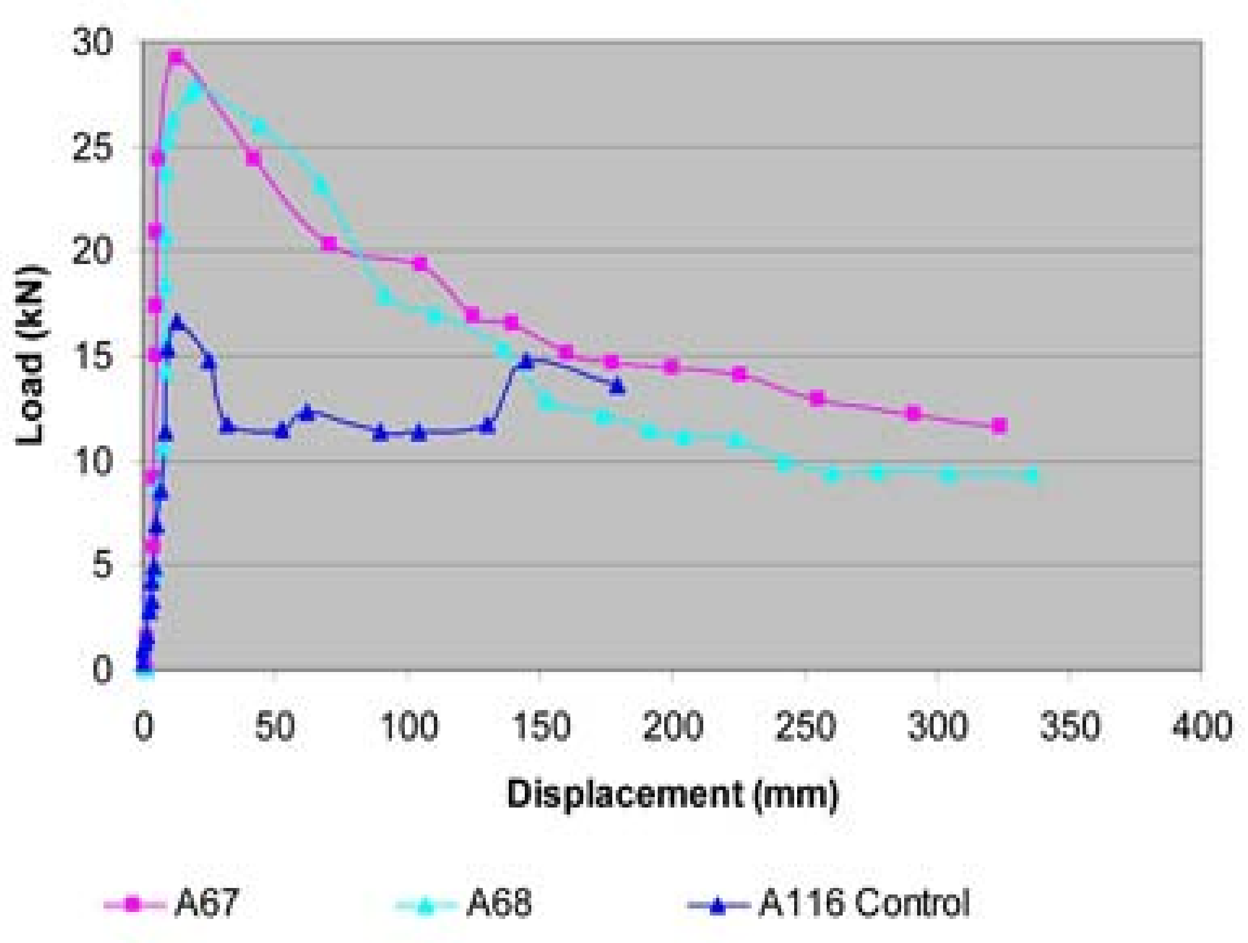
EKG treatment was designed to accommodate either of the identified failure mechanisms. The treatment was based around an array of EKG electrodes installed at 2m centres in the form of tessellating hexagonal cells, with the hexagon being defined by anode stations and a central cathode.

Upon application of a DC potential (60-80V) electroosmosis forced water to flow from the soil adjacent to the anodes to the cathodes. The treatment took only six weeks and resulted in:

- Dewatering from the cathodes >25 times that from control drains.
- A reduction in plasticity and shrinkage characteristics.
- An increase in groundwater temperature from 10OC to 20OC.
- A modest DC power consumption of only 11.5kWhrs/m3 of soil treated.
- Improvements in shear strength parameters (c′ and Φ′)
- A 263% improvement in the bond strength of the anodes acting as nails
- A cessation of slope movement.

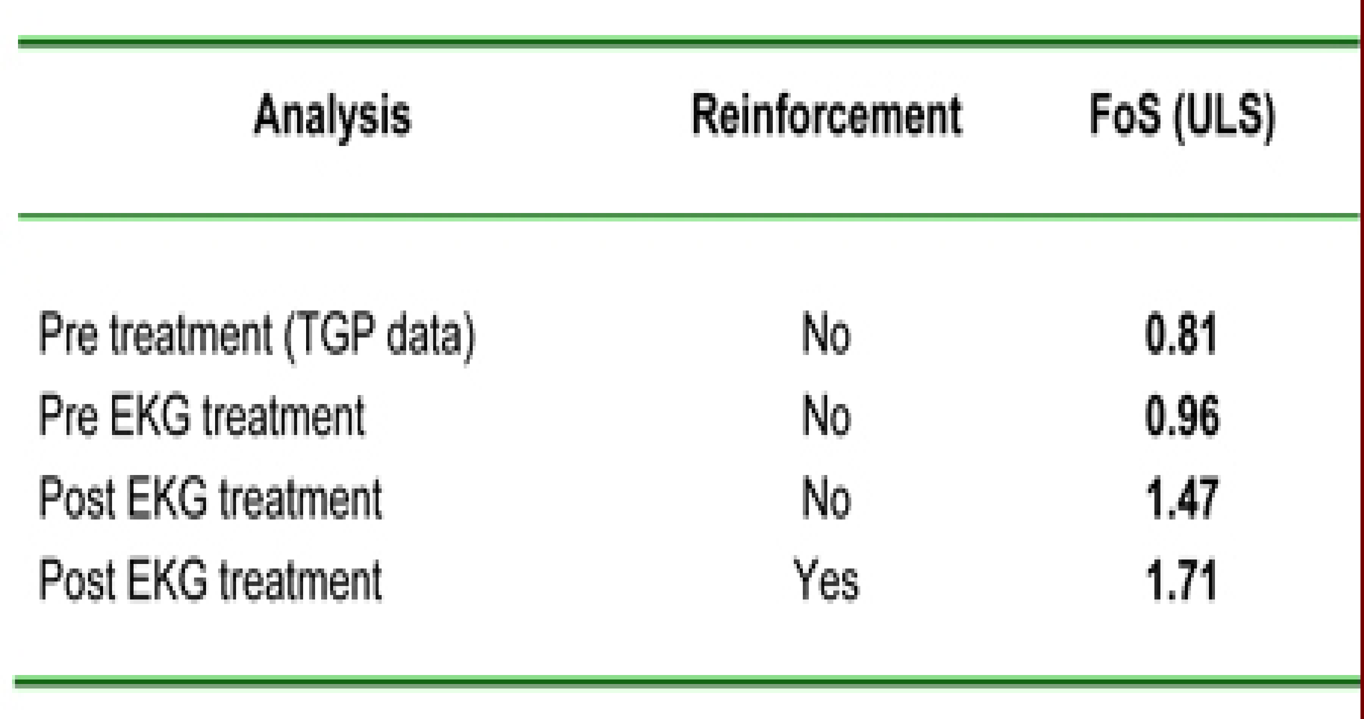
Following EKG treatment the anodes have been retained as permanent soil nails and the horizontal cathodes retained to act as permanent drainage.

Installation of EKG materials into a railway embankment



Comparison of pull out strength for electrokinetic and control reinforcement

Slope stability analyses were undertaken pre and post treatment. The analytical results are shown in the table below:



Analysis	Reinforcement	FoS (ULS)
Pre treatment (TGP data)	No	**0.81**
Pre EKG treatment	No	**0.96**
Post EKG treatment	No	**1.47**
Post EKG treatment	Yes	**1.71**

Longevity of treatment

The use of EKG to stabilise slopes is a long term solution because:

- Soft weak embankment materials consolidate and improve in shear strength with EKG treatment. This consolidation is permanent.
- Additionally, EKG treatment works best on these soft materials, which are critical to the stability, and in this way the treatment can be considered ‘self selecting’
- Modifications in soil clay chemistry such as cementation and plasticity occur under conditions induced by electroosmotic flow. Given the fine grained nature and very low transmissivity of the soil, the probability of the reversal of these changes is negligible and hence the effects are considered permanent.

- Enhancement of soil/reinforcement bond is a long term effect.
- Passive drainage (de-activated cathodes) is retained in the slope.

Costs

A cost analysis comparing slope stabilisation using the EKG method with the lowest cost alternative of gabion baskets and slope slackening, indicated that the EKG treatment produced total project cost savings of 26%.

Carbon Footprint

A carbon footprint comparison of the EKG and conventional treatment options showed 47% lower emissions by using EKG.

Induced currents

Issues have been raised regarding the possibility of ‘stray’ currents. For clarification, this term is used to denote electric currents which do not flow where intended and are caused by two mechanisms:

- Direct conduction
- Induced currents

An analysis of the EKG treatment indicated that such currents are negligible.

Benefits of EKG treatment

In summary, the benefits of EKG treatment include:

Effective method for slope stabilisation

➢Reduced cost

➢Reduced access requirements for labour and plant and materials

➢Reduced health and safety risk

➢Rapid deployment and low labour requirements

➢The treatment can proceed whilst maintaining the railway in service (as occurred during the trial)

➢Long term drainage of the slope can be provided for by the filtration and drainage functions of the EKGs in the passive mode.

➢Sustainability benefits including reduced carbon footprint and elimination of the use of primary aggregates.

Other benefits include:

- The treatment is gradual, only acts when current is on and does not induce rapid changes in ground conditions especially settlement. This therefore provides the option to cease treatment immediately if ever it were deemed necessary.
- The treatment can be flexible in approach by varying voltage, electrode spacing and duration of treatment.

Further flexibility will be possible by manipulating the electrode array and angle of electrode installation to accommodate in situ obstacles such as trees.

EKG reinforced soil wall, County Durham

The objective of the trial was to construct a reinforced soil wall constructed with super soft clay fill. In this application the EKG materials acted both as drainage paths and reinforcement.

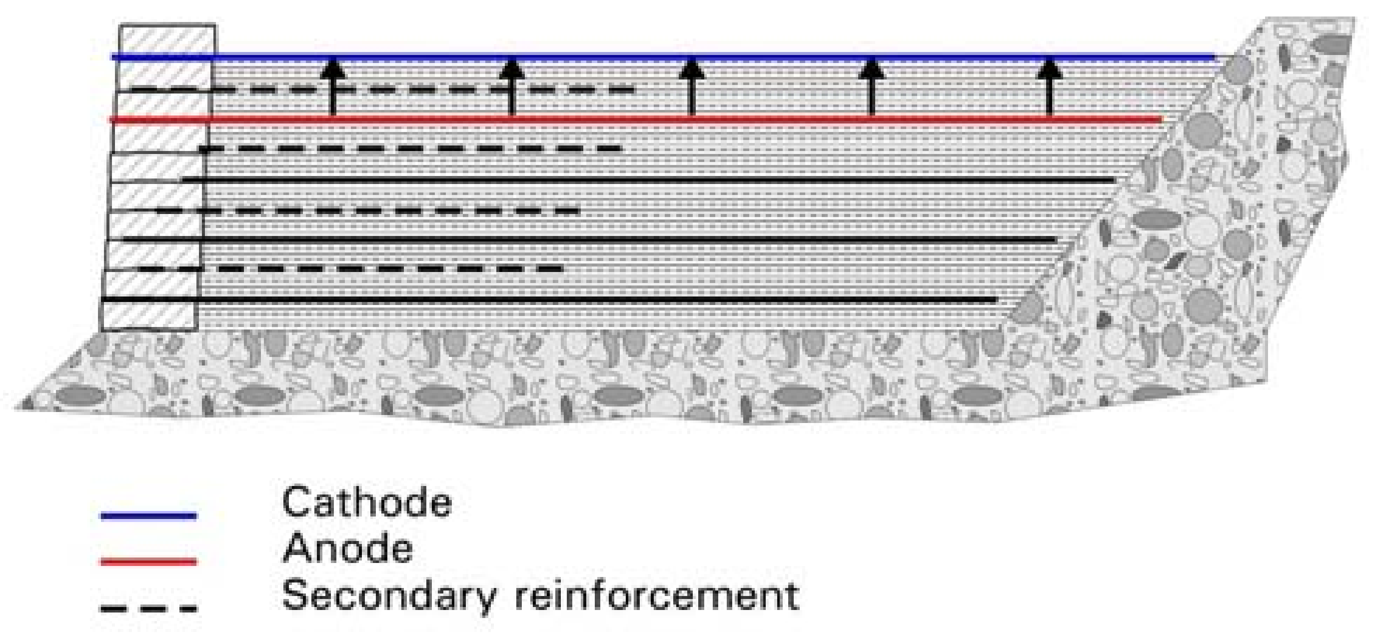
Most codes of practice do not permit the use of cohesive soils in the construction of reinforced soil due to potential problems of short term stability and its influence on the durability of metallic reinforcement. Short term stability results from low shear strength and poor bond between the reinforcement and the cohesive soil which is aggravated by the development of positive pore water pressures at the soil/reinforcement interface.

To illustrate the power of EKG to permit the use of material usually considered to be totally unsuitable, a reinforced-soil wall was constructed with fill in the form of a clay slurry (defined as a disturbed cohesive soil with a water content higher than the liquid limit).
The wall was constructed using a 'wraparound' design, utilising sandbags for the front face to temporarily retain the liquid fill. The ends of the trial wall were retained using conventional reinforced soil blocks, and the wall was raised using a staged construction technique. Clay slurry was prepared in a pit adjacent to the wall and poured in 300mm layers.

The above figure and the previous figures show the typical arrangements for the treatments

Preparation and pouring of super soft fill :

Each lift was constructed and dewatered vertically by electro-osmosis applied via horizontally placed EKG electrodes. Once a lift had been successfully treated then the next lift was constructed, the original cathode now becoming the anode, and the original anode being turned off and reverting to a reinforcing role.



Construction sequence of the reinforced soil wall:

The result of the trial showed that the shear strength of fill in the form of a wet slurry could be increased to permit safe construction of a vertical reinforced soil wall. Another finding was that the reinforcement/soil bond increases in proportion to the increase in shear strength.

This use of EKG technology offers the potential for the use of very poor quality materials which are ubiquitous and otherwise represent a liability rather than an asset.

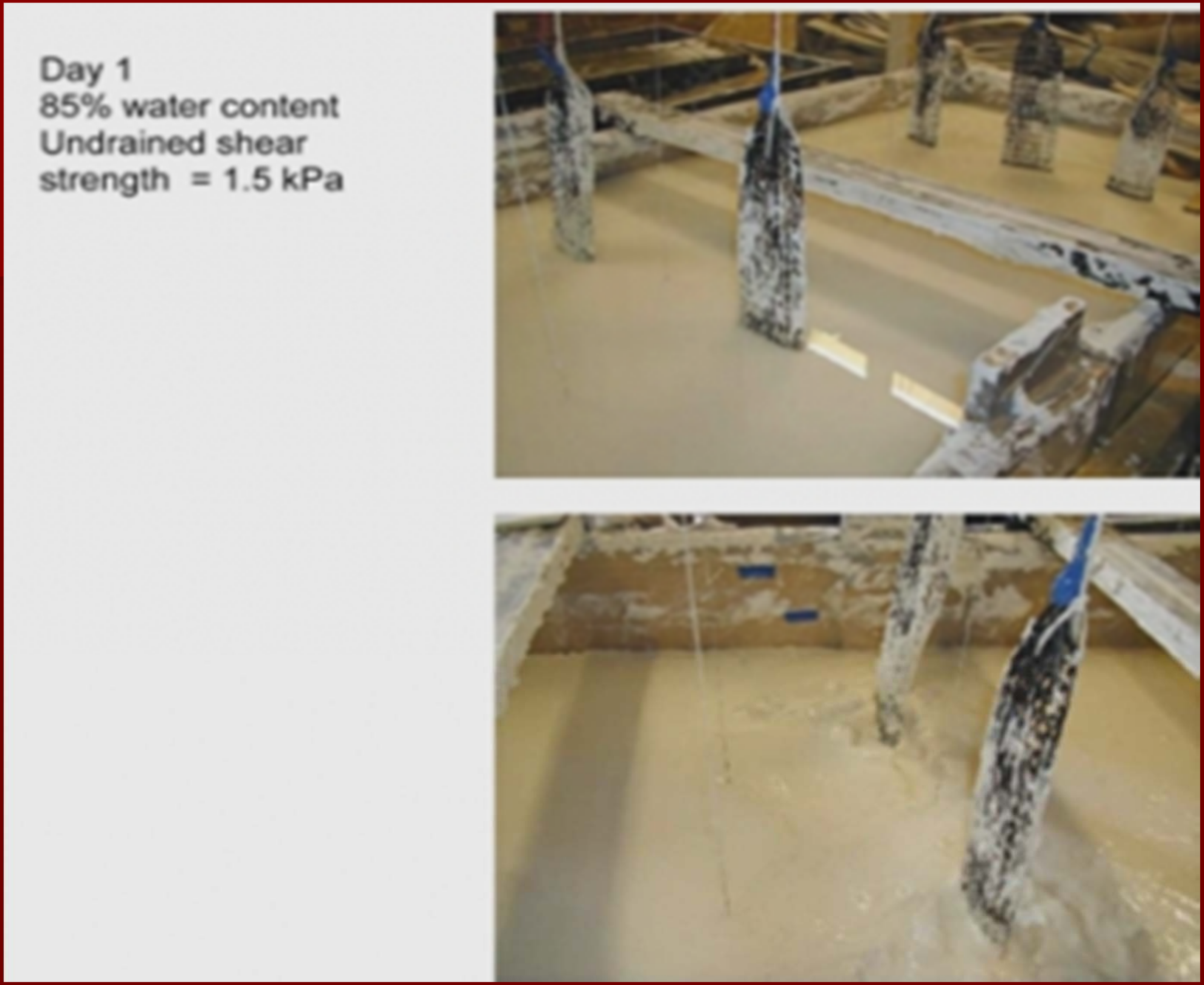
EKG reinforced wall after the construction of lift No. 3

3.Consolidation of super soft soil

EKG has been used in the form of an electrically conductive prefabricated vertical drain (e-PVD), to consolidate super soft kaolin clay. A large test pit was filled with kaolin clay with a moisture content of 85% to a depth of 2.4m with EKG vertical drains installed as shown in. The clay was left to settle for 100 hours, resulting in a consolidation of 20mm.

Electro-osmosis was then applied for a period of 500 hours which produced further consolidation of 340mm and an increase in shear strength from < 1kN/m² to 15–30kN/m². To produce an equivalent result using conventional means would have required a surcharge loading of 10m of fill, which would have been impossible to place on the super soft soil.

During electro-osmosis water flows from the anode to the cathode; as a result the area around the anodes experiences the greatest reductions in moisture content and improvement in shear strength. In order to minimise moisture content anisotropy, the trial was completed with a phase of polarity reversal in order to draw water away from the electrodes which were acting as anodes in the first phase. Polarity reversal resulted in a more even distribution of shear strength in the soil.



Day 1
85% water content
Undrained shear strength = 1.5 kPa

24 days having normal polarity

Day 40
62% water content
Undrained shear
strength = 35 kPa

16 days having reverse polarity

Large lab scale consolidation of super soft soil using EKG

The trial demonstrated that dewatering/consolidation using EKG prefabricated drains is rapid, effective and, energy efficient. For full scale applications, consolidation by EKG has a number of potential advantages over conventional wick drain technologies:

- It is faster
- No surcharge is required
- The effectiveness of the e-PVD is unaffected by kinking or smearing as consolidation proceeds

- Acknowledgements

- http://www.electrokinetic.co.uk/dewatering/

1. Plastic garden water butt used to store chemical solution;

2. 300 mm x 300 mm x100 mm excavation to allow electrode placement;

3. 40 mm OD hollow plastic tube used as float;

4. Top 200 mm insulated to prevent electrical bridging;

5. 65 mm OD perforated steel tube used as electrode;

6. Float valve.

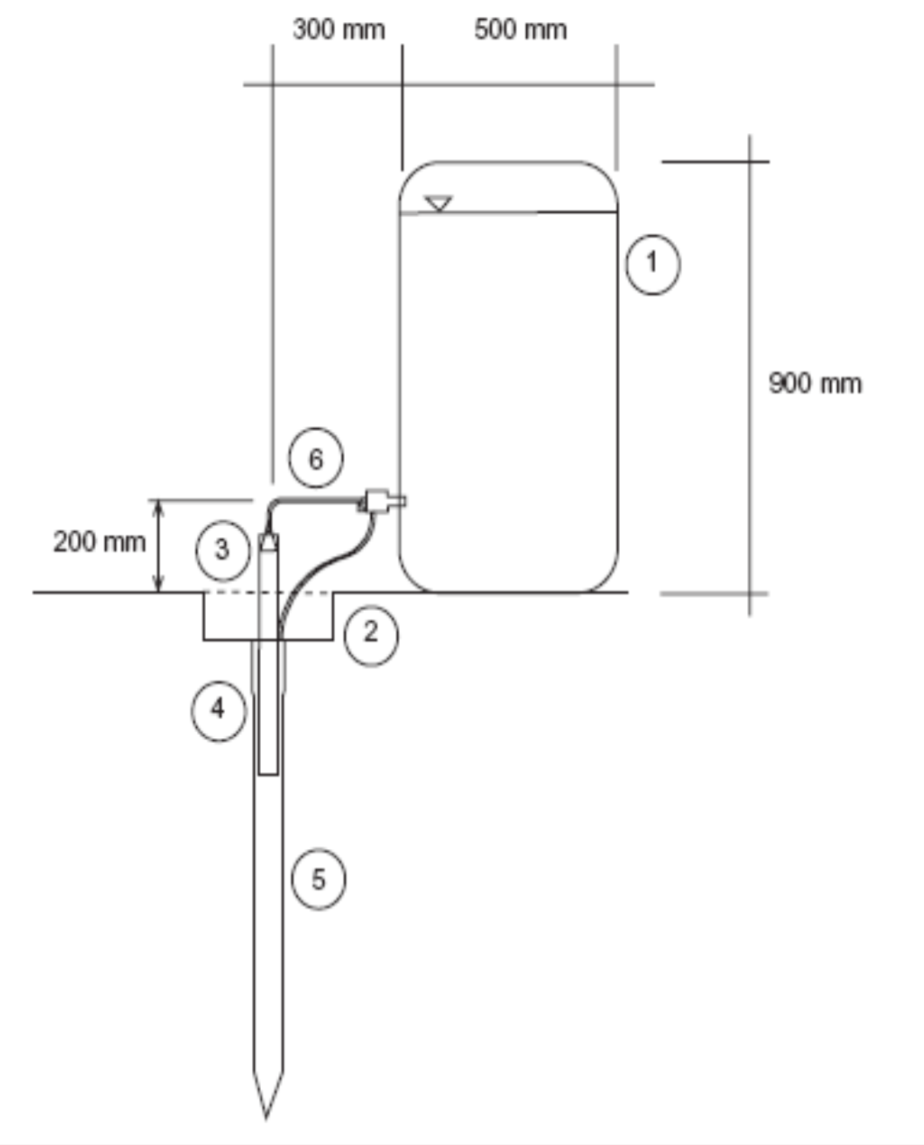


Fig. 5. Chemical feed arrangement to electrodes