Geotextiles and Geomembranes 44 (2016) 319–331

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Electrokinetic strengthening of slopes – Case history

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ARTICLE INFO

Article history:
Received 26 July 2015
Received in revised form
3 December 2015
Accepted 8 January 2016
Available online 4 February 2016

Keywords:
Electrokinetic geosynthetics
Strengthening of slopes
Case history

ABSTRACT

Traditional embankment stabilisation techniques can have severe environmental impacts during construction and frequently leave behind a stark legacy of a bare embankment unsuitable for wildlife and unsightly for local residents. Electrokinetic geosynthetic (EKG) strengthening of slopes is a multi-component treatment method which includes dewatering by electro-osmosis; reinforcement; drainage and soil modification. The method offers economic and environmental benefits.

This paper provides a brief review of the electrokinetic concept as it applies to failed slopes and illustrates the method with respect to the design, analysis, construction and verification of the stabilisation of a strategically important and environmentally sensitive highway embankment. The strengthening of the slope was achieved with a 29% reduction in cost and a 40% reduction in carbon footprint when compared to an adjacent embankment which had been remediated a year earlier using conventional soil nails. Following the repair the scheme was awarded an Institution of Civil Engineers Award for Innovation and a Green Apple Award for excellence in sustainable construction.

1. Introduction

The ability of electrokinetic phenomena to transport water, charged particles and free ions through fine grained low hydraulic permeability soils was identified over two hundred years ago (Reuss, 1809). In 1939 Casagrande demonstrated that applying an electrokinetic force to fine grained soils with high water contents resulted in an increase in effective stress within the soil through the generation of negative pore water pressures (Casagrande, 1949, 1952, 1983). Casagrande used electro-osmosis to increase soil shear strength and thus stabilise steep cuttings. Similar studies have been described by Fetzer (1967), Chappell and Burton (1975) and Wade (1976); however, the widespread application of electrokinetic stabilization of slopes has been limited owing to three technical issues:

1. Application in inappropriate geotechnical settings
2. Ineffective control of boundary conditions
3. Ineffective electrodes

These technical problems have been reduced significantly by the development of electrokinetic geosynthetics (EKG).

Conventional geosynthetics play a ***passive or reactive*** role, e.g. reinforcement provides tensile resistance, but only after an initial strain has occurred and geosynthetic drains provide a passage for water but do not cause the water to flow towards the drain. In 1994 it was postulated that new applications for geosynthetics was possible if they could provide an ***active*** role, initiating biological, chemical or physical change to the matrix in which it they were installed as well as providing the established functions. It shown that this is possible by combining the electrokinetic phenomena of electro-osmosis, electrophoresis and associated electrokinetic with the traditional geosynthetics functions of drainage, filtration, containment and reinforcement to form electokinetic geosynthetics (EKG). The EKG concept and its application have been described by a number of authors including (Jones, 1996; Jones et al., 1997; Nettleton et al., 1998; Shang, 1998; Abiera et al., 1999; Rowe and Jones, 2000; Pugh et al., 2000; Jones, 2001; Hamir et al., 2001; Jones and Pugh, 2001; Pavlakis et al., 2001; Lamont-Black et al., 2001; Pugh, 2002; Chew et al., 2004; Lorenzo et al., 2004; Glendinning et al., 2005; Jones et al., 2005, 2008; Ritterong et al., 2008; Lamont-Black et al., 2010; Jones et al., 2011; Karunaratne, 2011; Zhuang et al., 2014; Bourges-Gastand et al., 2015; Lamont-Black et al., 2015; Lamont-Black and Jones, 2015; Zhaung, 2015).

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http://dx.doi.org/10.1016/j.geotexmem.2016.01.001
0266-1144/

Notation

A_v	Avogadro constant
A	adhesion (kN/m)
$c'-\Phi'$	effective shear strength parameters
c'_{des}	effective cohesion of bulk soil (kPa)
c'_{int}	effective cohesion at junction between anode and bulk soil (kPa)
C_u	undrained cohesion (kPa)
e_{ch}	electronic charge
e	void ratio
E_c	electrical conductivity (mS/m)
EO	electro-osmotic consolidation (MN/m^2)
Fe_{ram}	relative atomic mass of iron
IFS	shear strength as measured at the junction between anode and bulk soil (kPa)
I_p	plasticity index
k_e	coefficient of electro-osmotic permeability (m^2/sV)
k_h	coefficient of hydraulic conductivity (m/s)
LL	liquid limit
M	mass lost
MG	made ground
m_v	coefficient of volume compressibility (MN/m^2)
n	porosity
PL	plastic limit
Q_e	charge passed
r_u	pore water pressure coefficient
S	Siemens
-u	pore-water suction (kN/m^2)
V	applied electrical potential (V)
v	oxidation valence of iron
W_e	water content
γ_w	unit weight of water (kN/m^3)
Φ'_{des}	effective angle of friction of bulk soil (degrees)
Φ'_{int}	effective angle of friction at junction between anode and bulk soil (degrees)
ε_w	water permittivity (F/m)
μ	viscosity (Ns/m^2)
ζ	zeta potential (V)

Electrokinetic geosynthetic (EKG) strengthening of slopes is a multi-component treatment method. Treatment is initiated by the installation of an array of electrokinetic geosynthetic (EKG) anode and cathode electrodes (Fig. 1). The EKG anodes are formed as porous tubular metal elements through which conditioning fluids can be introduced. The cathodes are formed as geosynthetic drains with a filtration element to prevent blockage and contained within a conductive mesh. Once installed the anodes and cathodes are connected to a computer controlled DC power supply for a period of electrokinetic treatment. The concept of electrokinetic geosynthetic strengthening of failed or failing slopes has been described by Pugh (2002), Jones et al. (2005), Zhaung (2005), Zhaung et al. (2006), Jones et al. (2008), Jones (2011), Mumtaz and Girish (2014), Alder et al. (2015) and Jones and Lamont-Black (2015). The economic and environmental benefits of electrokinetic strengthening of slopes have been described by Jones et al. (2014). This paper provides a brief review of the electrokinetic concept as it applies to failed slopes and illustrates the method with respect to the design, analysis, construction and verification of an award winning Case History.

2. Electrokinetic geosynthetic strenghtening of slopes

Electrokinetic geosynthetic slope stabilisation is a multifunctional system comprised of four components; dewatering by electro-osmosis; reinforcement; drainage and soil modification.

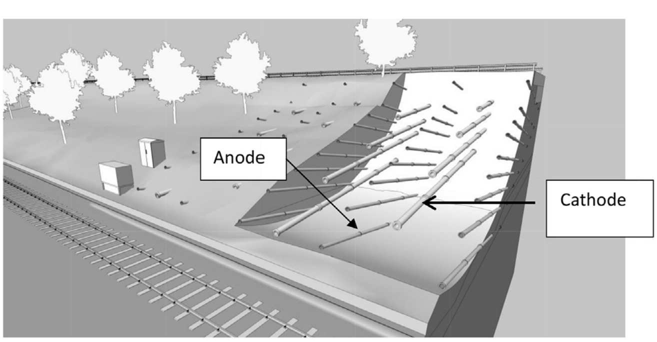

Fig. 1. Electrokinetic slope stabilisation with anode/nail and cathode/drains.

Electro-osmosis – An applied voltage gradient in a soil creates electro-osmotic flow from the anode to the cathode. By draining the cathode and preventing water ingress at the anode, there is a major drop in pore-water pressure which causes an immediate increase in effective stress. In addition, ion migration from the anode results in cementation. The cementation causes a reduction in the plasticity and an increase in cohesion of the soil. The water removed by electro-osmosis is both interstitial water and vicinal water. Interstitial water is controlled by capillary forces. Vicinal water consists of water molecules layered on the clay particles which can be removed by electro-osmosis. Returning this water to the clay soil can only be achieved by electro-osmosis using polarity reversal (Vesilund, 1994; Smith and Vesilund, 1995; Vesilund and Hsu, 1997).

Although most soils used in civil engineering are suitable for electro-osmotic treatment a detailed analysis of acceptance criteria has been provide by Pugh (2002) (Table 1).

Reinforcement – During electrokinetic treatment ion migration from the anode can be enhanced or controlled by selecting the structure and composition of the anode together with the optional use of conditioning fluids. Cementing around the anode increases the anode/soil bond referred to as the interface shear strength (IFS). The cemented zone also provides improved frictional characteristics in the soil. The enhanced bond increases the pull out resistance of the anode/soil nail and has been shown to be permanent (Milligan, 1995).

Drainage – During electrokinetic treatment, water flows towards the cathodes resulting in drainage of the slope. By retaining the cathodes as permanent geosynthetic drains, wetting up of the slope is combated. It has been demonstrated that drainage of soil is as effective as the provision of reinforcement in increasing strength (Heshmati, 1993; Jones, 2010). Drilled drainage systems which can be installed horizontally into slopes reduce pore water pressures sufficiently to eliminate the risk of delayed collapse (Geotechnical Consulting Group, 1993). EKG cathode drains provide a similar function post electrokinetic treatment but have the added advantage of including a filter membrane to guard against long term clogging which is a concern identified by Hutchinson (1977). The filter is protected by a stainless steel mesh. In addition, the length of the horizontal drains can be extended beyond the length required