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Research paper

Soil improvement by electroosmotic grouting of saline solutions with vacuum drainage at the cathode

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ABSTRACT

Electroosmotic grouting is a ground improvement method for soft soils that is not widely accepted for common application because the improvement of soil strength is not uniform. This paper proposed a new method to improve the non-uniform effect of electroosmotic grouting. Such method is electroosmotic grouting coupled with vacuum drainage at the cathode. The experimental study shows that the treatment effect of electroosmotic grouting with vacuum drainage at the cathode is not only better than general electroosmosis methods but also more uniform than such methods. In this study, the soil strength increased by 362%, 350%, and 438% at the locations close to the anode, between the anode and cathode, and close to the cathode, respectively. The results demonstrate that this technique could improve the treatment effect of electroosmotic grouting in soft soils.

1. Introduction

The electroosmosis phenomenon in soils was first reported by Reuss in 1809; it involves the insertion of electrodes in the soil and the passage of a direct current through the soil. When the soil particles are in contact with water, electric double layer (as described by Gouy and Chapman(Mitchell, 1993)) is formed at the soil particle/water interface. The ions in the diffusion layer below the imposed electric field migrate toward electrode of opposite charges and cause the water molecules to move together as ions are naturally hydrated. So, the water content is reduced and the strength of the soil is increased (Fig. 1). It was not applied to geotechnical engineering until 1952 when Casagrande (1952) engineered electroosmotic soil consolidation and dewatering in slope reinforcement. Several successful case histories and research followed to explore the characteristics of electroosmosis (Bjerrum et al., 1967; Lo et al., 1991; Estabragh et al., 2014). In order to increase the effect of electroosmosis, the electroosmotic grouting was first introduced by Gray and Schlocker (1969) and Gray (1970), who investigated the electroosmotic transport mechanism for hardening soft soil using aluminum ion. Using this method, the liquid limit of montmorillonite dropped to about half the initial value, and the liquid limit of illite did not significantly change. Sutton and Alexander (1987) used electroosmosis to draw chemicals from anode to cathode for soil stabilization. Ozkan et al. (1999) investigated the injection of phosphate and aluminum ions at the cathode and anode to improve the mechanical properties of kaolin. Their results showed a 500–600% increase in kaolinite undrained shear strength in the treated samples, but the strength increase was not homogeneous throughout the specimen. Lefebvre and Burnotte (2002) showed that injection of saline solution to increase the soil conductivity at the soil-electrode contact can double the electrical potential effectively transmitted to the soil and improve the performance of electroosmotic consolidation. Alshawabkeh and Sheahan (2003) reported that injection of phosphate acid solutions under the electric field will increase the stability of soft soil. Mohamedelhassan and Shang (2003) used 15% $CaCl_2$ and 10% $Al_2(SO_4)_3 \cdot 18H_2O$ to improve soft soil. Their results showed the significant effect of electro migration in transporting the cations in the permeating solutions from the anode to the cathode. Asavadorndeja and Glawe (2005) injected calcium ions into soil coupled with depolarization technique and found that the soil strength increased up to 170% immediately after treatment and up to 570% after curing for 7 days. Otsuki et al. (2007) injected Mg $(CH_3COO)_2$, $MgSO_4$, $Mg(NO_3)_2$, $ZnSO_4$, and $AgNO_3$ as anolyte solutions and NaOH and Na_2CO_3 as catholyte solutions into kaolinite and obtained an increase of shear strength up to 300 kPa without applied load. Chang-Yu Ou et al. (2009) proved that the effect of electroosmosis on silty clay can be enhanced and the treat time reduced by injecting saline solutions during electroosmosis,

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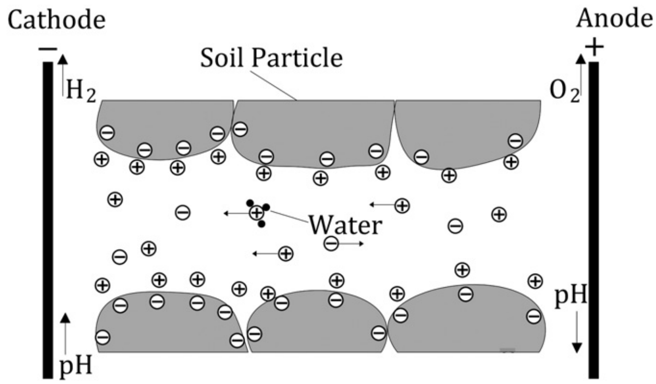

Fig. 1. Principles of electroosmosis.

but the improvement was limited to the area near the anode. Building upon this work, Shao-Chi Chien et al. (2010) added a relay pipe to inject sodium silicate between the anode and cathode, the results of which showed that the region of improvement was expanded.

The literature suggests that electroosmotic grouting is effective in strengthening soft soil with the following caveats: the improvements are not homogeneous. There were apparent low improvement regions near cathode after treatment, and sometimes, when saline was injected from cathode, soil near the anode became relatively weak. This is attributed to the acidic and alkaline conditions developed around the anode and cathode, in which the chemical reaction between injection chemical solutions and soil would produce cementing agents under specific pH environments (Alshawabkeh and Acar, 1996; Alshawabkeh et al., 2004; Asavadorndeja and Glawe, 2005). In addition, with regard to drainage, water content of soil near the cathode was reduced very little, and the high water content in soil limits the effect of improvement, especially near cathode.

To improve the inhomogeneous effect in electroosmotic consolidation, Lo et al. (1991) used electrode polarity reversal to make soil strength between the electrodes homogeneous. However, Tao et al. (2014) pointed out that the polarity reversal will have an indistinctive effect because the electrode interface resistance will increase sharply after polarity reversal, resulting in low current and inefficient energy. Peng et al. (2013) applied vacuum preloading combined with electroosmosis leading to significant and uniform improvements in soil strength through appropriate arrangement of electrodes and PVDs (prefabricated vertical drains). However, the practical application of vacuum preloading combined with electroosmosis is difficult because the membrane used in vacuum preloading must be kept sealed air tight, but the large number of electric wires and electrodes under the membrane will likely puncture the membrane, which will result in the failure of vacuum preloading.

The primary objective of this study is to evaluate electroosmotic grouting by saline solution with vacuum drainage at the cathode, the area of weakest improvement, so the full field vacuum preloading with electroosmosis is not necessary. In this study, vacuum pressure about −30 kPa was conducted at the cathode. This vacuum pressure has two benefits: 1) it accelerates the drainage of pore water and air bubbles, improving the treatment of soil near cathode; and 2) it accelerates the saline solution flow from anode to cathode due to the pressure difference between the two. Calcium chloride was chosen as the grouting solution from anode due to advantages such as non-toxicity, non-contamination, and low cost. Kaolinite is used in this study because it is one of the most common minerals in the earth and often used in research (Acar et al., 1997; Ozkan et al., 1999; Otsuki et al., 2007; Estabragh et al., 2014) to represent soft soil. Treatment effect and further understanding of mechanism were investigated through monitoring of samples' settlement, drainage, strength, chemical elements or concentration of soil particles, precipitation, and pore water.

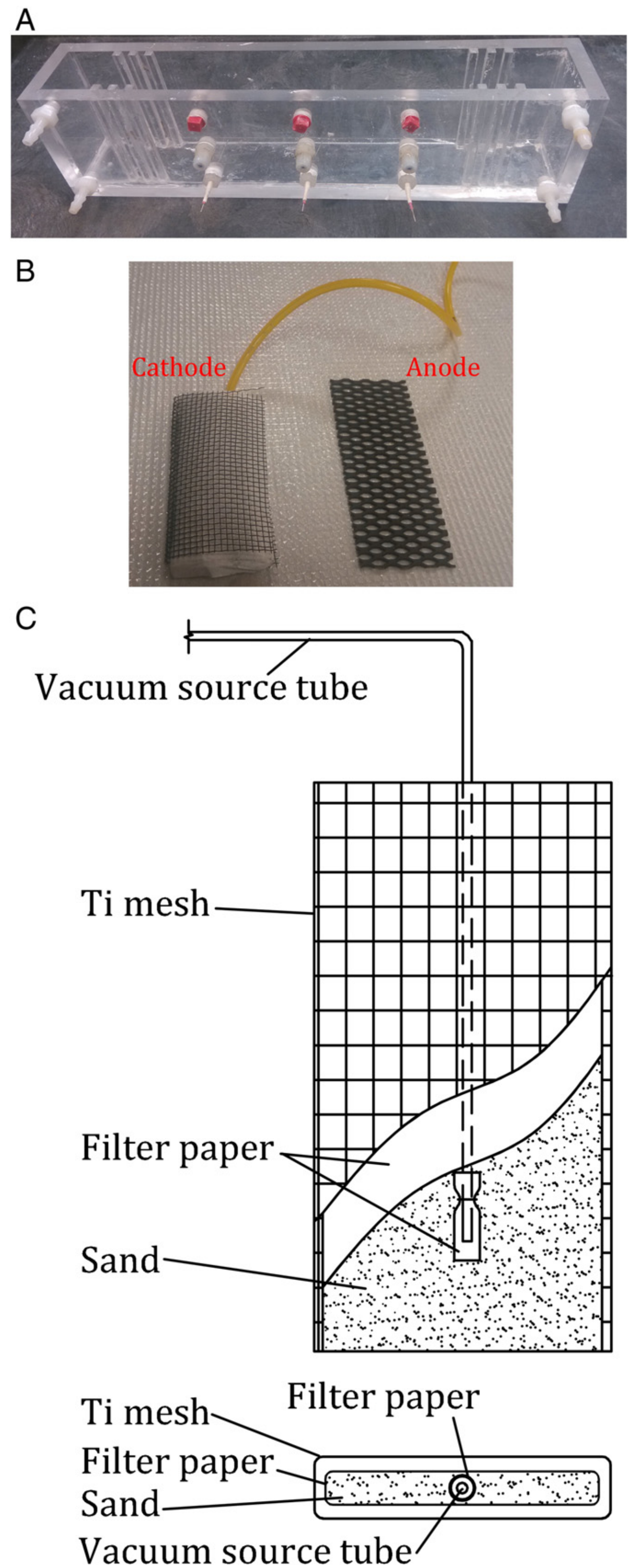

Fig. 2. (A) Electroosmosis cell, (B) electrodes, and (C) schematic of cathode.