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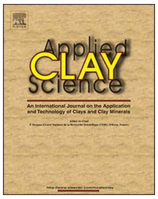

Research paper

Experimental-artificial intelligence approach for characterizing electrical resistivity of partially saturated clay liners

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ABSTRACT

The aim of this study is to investigate the evolution of electrical resistivity of different kaolinite-dominant clay liners, in terms of its soil composition, as its moisture content and dry density change. Eight different mixtures of Kaolin-Bentonite (90%K-10%B; 80%K-20%B; 70%K-30%B; 60%K-40%B), and Kaolin-Sand (90%K-10%S; 80%K-20%S; 70%K-30%S; 60%K-40%S) were tested in this study. Artificial Neural Network, ANN, method was used to develop an electrical resistivity model using the experimental results. The developed model offers the required level of generalization to analyse and assess precisely the effects of different variables on the electrical resistivity of kaolinite-dominant clay liners. The outcomes of this study highlight the effects of water content, soil composition, and dry density on the electrical resistivity of soils. The results in this study show that, at low water content, the adsorbed water and interparticle contacts provide continuous pathways for electrical flow through the soil. Furthermore, the results also indicate that increasing the bentonite content in the mixture decreases its electrical resistivity whereas increasing the sand content increases its electrical resistivity. This behaviour could be attributed to the highest surface conduction of bentonite clay compared to sand. For the soil mixtures tested in this study, the results also show that increasing the dry density of the soil by 20% could result in 50% reduction in its electrical resistivity. This behaviour could be explained in terms of the expected increase in number and area of interparticle contacts as dry density increases that could also improve soil pore water connectivity.

1. Introduction

The need to design and construct safe and environmentally friendly landfill waste disposal facilities is crucial to protect the surrounding environment, particularly groundwater, from the waste pollutants contained in the landfill facilities. The bottom engineered liner is one of the critical structure elements in the landfill as it serves as a hydraulic barrier to retard migration of landfill leachate into underlying aquifer. Therefore, the landfill's engineered liner should be made of low permeable materials. One of the possible configurations of landfill liner includes a low permeability compacted clay layer in conjunction with a synthetic liner such as geomembrane (Lake and Rowe, 2005; Bouazza, 2002).

Traditionally, swelling clays such as bentonite have a very low hydraulic conductivity in the range of 10^{-11} to 10^{-12} m/s; these clays have been the preferred clay for use in liners (Zhao et al., 2017; Di Emidio et al., 2017). However, bentonite clays are not easily available in some regions such as Southeast Asia (Karunaratne et al., 2001). Furthermore, bentonite clays are highly susceptible to moisture and volume changes under heating/cooling and drying/wetting cycles causing instability problems (Mitchell and Soga, 2005; Di Maio et al., 2004; De Camillis et al., 2017; Ören and Akar, 2017; Polanský et al., 2017). Such changes could threaten the integrity of liner as it could lead to shrinkage cracks.

Several researchers show that man-made kaolinite-dominant clay liners could be used as an alternative to bentonite clay liners (Elliott and Watkins, 1997; Karunaratne et al., 2001; Li et al., 2014). In general kaolinite-dominant clays consist of mixture of Kaolin-Bentonite (K-B) or Kaolin-Sand (K-S), although the compositions may vary widely from deposit to deposit. The addition of bentonite could reduce the hydraulic conductivity of the liner and improve its contaminant retention behaviour whereas the addition of sand could enhance the mechanical properties of the liner (Karunaratne et al., 2001; Dolinar, 2009a,b; Watabe et al., 2011; Deng et al., 2017).

In fact, construction of homogeneous compacted clay liner having uniform low hydraulic conductivity throughout the entire liner is a

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challenging task as the hydraulic conductivity is sensitive to compaction conditions in terms of compaction effort, moisture content, soil grading/composition. Therefore, a quality-control technique is required to assess the level of homogeneity of the constructed compacted clay liner. Several geophysical methods such as electrical resistivity imaging (ERI), seismic refraction (SR), ground penetrating radar (GPR) and multiple-channel analysis of surface waves (MASW) can be used to evaluate the soil profile as they are relatively inexpensive, fast, and non-destructive mapping techniques. In general, these methods produce measurements which are related to some physical properties of the subsurface and its spatial distribution. The working principles of various geophysical methods can be found in Telford et al. (1990) and Reynolds (1997).

Several studies have compared the performance of these methods in determining the changes in the soil properties and types (Hirsch et al., 2008; Missiaen et al., 2008; Groves et al., 2011). However, ERI is recommended to assess the level of homogeneity of the constructed compacted clay liner due to its low cost and the high sensitivity of the electrical resistivity of soils to changes in soil density, moisture content, and composition on (Abu-Hassanein et al., 1996; Besson et al., 2004; Corwin and Lesch, 2005; Seladji et al., 2010; Kibria and Hossain, 2012; Li et al., 2014). In fact, these changes are the possible source of heterogeneity in the constructed compacted clay liner. Therefore, understanding the relationships between electrical resistivity, ER, of compacted clay liner and their physical properties (soil composition, unit weight, and water content) are crucial to obtain a meaningful electrical resistivity survey for clay liners.

Several studies have examined the relationships between ER of soil and their physical properties (Archie, 1942; Gupta and Hanks, 1972; Rhoades et al., 1976; Kalinski and Kelly, 1993; Abu-Hassanein et al., 1996; McCarter and Desmazes, 1997; Revil et al., 1998; Seladji et al., 2010; Beck et al., 2011; Kibria and Hossain, 2012). However, to the authors' knowledge the electrical resistivity behaviour of partially saturated man-made kaolinite-dominant clay liner has not been investigated yet. The main objective of this study is to understand the role of soil composition (mix ratio), dry density, and moisture content in determining ER of kaolinite-dominant clay liner. For this purpose, an extensive laboratory study was conducted to measure ER of eight different mixtures of Kaolin-Bentonite (K-B), and Kaolin-Sand (K-S) at different water contents and dry densities. Then the laboratory test results were used to develop an electrical resistivity model for kaolinite-dominant clay using Artificial Neural Network, ANN. The developed model was used to conduct a parametric sensitivity study to assess the role of different variables on ER of kaolinite-dominant clay liner.

Artificial Neural Network was used in this study as it has several advantages over the conventional regression methods (Tu, 1996; Sargent, 2001; Yu et al., 2006; Liew et al., 2007; Liu et al., 2009). In fact, the regression methods involve predefining a certain function (e.g. polynomial, power, or exponential), then fine-tune the shape of the parametric function to fit the observed data. Therefore, they are fundamentally limited in their ability to use complex high-dimensional functions (Bengio and LeCun, 2007). However, ANN model can implicitly detect complex nonlinear relationships between independent and dependent variables and also has the ability to detect all possible interactions between the model parameters. Furthermore, ANN does not impose any restrictions on the input variables such as how they should be distributed. Therefore, ANNs can better model the nonlinearity of noisy or incomplete data. Finally, it should be mentioned that ANN has been successfully applied to many applications in geotechnical engineering to model multivariate non-linear complex behaviour (Abu Kiefa, 1998; Juang et al., 2001; Goh et al., 2005; Hanna et al., 2007; Abuel-Naga and Bouazza, 2011, 2014).

Table 1
Properties of soils.

Properties	Kaolin	Bentonite
Liquid limit (%)	74	504
Plastic limit (%)	32	53
G_s	2.58	2.68
Cation exchange capacity (meq/100 g)	0.075	80
Surface charge density (μC/m^2)	0.36	10.24
Main chemical composition (weight %)		
SiO_2	45.2	63.8
Al_2O_3	38.8	13.6

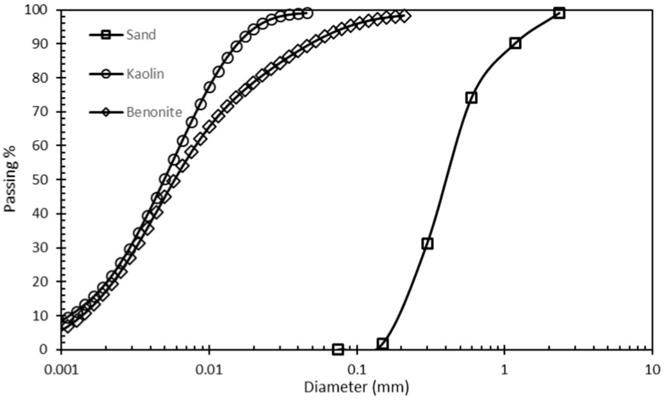

Fig. 1. Particle size distributions of sand, kaolin and bentonite.

2. Laboratory testing

2.1. Materials and experimental program

The geotechnical properties of kaolin and bentonite clays used in this study are listed in Table 1. Fig. 1 shows the particle size distribution of the clays and silica sand used in this study. The specific gravity, minimum and maximum void ratios of the sand used in this study are 2.65, 0.58, 0.97, respectively. Eight kaolinite-dominant clay mixtures, as listed in Table 2, were tested in this study to understand the effect of coarse-grained soil (sand) and swelling clay (bentonite) on the ER of kaolinite-dominant clay mixtures. The experimental program was designed to characterize the geometric features of the Electrical Resistivity Constitutive Surface, ERCS, of each kaolinite-dominant clay mixture within the electrical resistivity (ER)-moisture content (w_c)-dry density (ρ_d) domain as shown in Fig. 2. For this purpose, a constant moisture content testing approach was adopted in this study. This approach involves measuring the electrical resistivity of a sample having a certain constant w_c as its ρ_d changes. Table 3 lists the different constant moisture contents and dry densities of the test samples for each type of mixture tested in this study. According to Table 3, the laboratory experimental program in this study includes 176 electrical resistivity measurements conducted for different kaolinite-dominant clay mixtures at different w_c and ρ_d levels.

Table 2
Kaolinite-dominated mixtures (by weight).

Mixture no.	Kaolin (K) %	Sand (S) %	Bentonite (B) %
1	90	10	0
2	80	20	0
3	70	30	0
4	60	40	0
5	90	0	10
6	80	0	20
7	70	0	30
8	60	0	40