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Effect of state of compaction on the electrical resistivity of sand-bentonite lining materials

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ABSTRACT

Sand-bentonite mixtures are often used as lining materials in various containment systems. Leachate leakage can affect the electrical resistivity of sand-bentonite liners, and consequently, resistivity measurements can be used as an effective tool to detect contamination. This paper presents the results of an investigation into the effect of the state of compaction on the resistivity of sand-bentonite mixtures, with the bentonite content varying from 0 to 100%. The resistivity of mixtures at their different states of compaction are investigated. The resistivity of the lining mixture decreases as the water content increases, but the rate of decrease is reduced significantly above a specific water content for each mixture. Furthermore, this specific water content was noted to be on the wet-side of the optimum for sand-bentonite mixtures and on the dry-side of the optimum for pure sand and pure bentonite. Increasing bentonite over 20% demonstrates insignificant impact on resistivity. It is observed that at higher water contents, bentonite addition has negligible effect on resistivity. Correlations applicable to the sand, bentonite and pore fluid used in this study have also been presented. The results from this study may be useful for soil contamination detection, liner leak detection, development of sensors, soil and corrosion studies, etc. in Australia as well as worldwide for similar sands.

Notation

γ_{dmax}	maximum dry unit weight (kN/m^3)
γ_{dmin}	minimum dry unit weight (kN/m^3)
γ	total unit weight (kN/m^3)
θ	volumetric water content (dimensionless)
ρ	resistivity of the soil specimen (Ωm)
σ	bulk conductivity of soil (S/m)
σ_w	pore water conductivity (S/m)
a	constant (Ωm)
b	constant corresponding to a soil type and pore fluid (dimensionless)
p_b	bentonite content (dimensionless)
c, m	fitting parameters (dimensionless)
A	cross-sectional area (m^2)
C_c	coefficient of curvature (dimensionless)
C_u	coefficient of uniformity (dimensionless)
p	percentage of clay fraction in soil (dimensionless)
D_{10}	effective size (mm)
G_s	specific gravity (dimensionless)
L	length of the test specimen (m)
m_b	mass of bentonite (kg)
m_s	mass of sand (kg)
R	resistance (ohm, Ω)
V	potential difference across the outer conductors/input voltage (V)
w	gravimetric water content (dimensionless)
w_l	liquid limit (dimensionless)
w_p	plastic limit (dimensionless)
w_{opt}	optimum water content (dimensionless)
w_T	specific value of water content at which the trend of the resistivity curve changes (dimensionless)

1. Introduction

Lining systems are used widely by waste storage and handling facilities to isolate contaminants and ensure that their effect on the environment is negligible (Fityus et al., 1999; Rowe et al., 2004; Rowe, 2012). The potential impact of the waste handled by a specific site determines the type of lining system to be employed (Shah, 2000). The liners are designed such that they have a very low hydraulic conductivity

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($<10^{-9}$ m/s). Geosynthetics as the man-made materials, such as geomembranes, geotextiles, and geosynthetic clay liners (Shukla, 2016), or natural materials, such as compacted clays (Daniel, 1984; Harrop-Williams, 1985; Chapuis, 2002), silty soils (Holtz, 1985), mine tailings (Jessberger and Beine, 1981), and sand- bentonite mixtures (Chapuis, 1990), can be used to make liners. This paper focusses on the liners made from bentonite and sand-bentonite mixtures.

Undoubtedly, the integrity of liners over their intended lifespan is vital. To guarantee adequate performance of liners, it is essential to account for the fact that liners are subject to harsh operating conditions, and they are likely to develop defects (Daniel, 1984; Oh et al., 2008; Rowe, 2005; Rowe, 2012; Shukla, 2016; Sirieix et al., 2016; Baawain et al., 2018). Consequently, the leachates are prone to leak out and contaminate underlying soil and groundwater. This necessitates the use of appropriate methods for the early detection of leakage and liner defect issues to ensure the timely control and mitigation of contamination. The electrical resistivity method, which is cost-effective and easy to use, can assist in solving this problem (Oh et al., 2008; Bai et al., 2013; Choo et al., 2016; Merritt et al., 2016; Sirieix et al., 2016; Wang et al., 2017; Baawain et al., 2018; Chu et al., 2018). This method is based on detecting the changes in the electrical resistivity of geomaterials, produced due to the addition of even a small amount of contaminant (Darayan et al., 1998; Yoon and Park, 2001; Pandey and Shukla, 2017). Furthermore, the electrical conductivity of soil depends on its properties (such as porosity, degree of saturation, composition of pore fluid, etc.), state of compaction, mineralogy, structure and temperature (Abu-Hassanein et al., 1996; Mitchell and Soga, 2005; Bai et al., 2013) as well as on the composition of the pore fluid (Fukue et al., 1999; Cardoso and Dias, 2017).

Besides their use in liner leak detection, there are additional applications of soil resistivity studies in geotechnics and especially in earthworks, such as anomaly detection (Panthulu et al., 2001), determination of soil state properties (Archie, 1942; McCarter, 1984; Kalinski and Kelly, 1993; Abu-Hassanein et al., 1996; Shah and Singh, 2005; Long et al., 2012; Kibria and Hossain, 2014; Choo et al., 2016; Merritt et al., 2016; Chu et al., 2018), locating liner leakages (Darilek and Parra, 1989; Pandey et al., 2017), soil contamination detection (Oh et al., 2008; Pandey and Shukla, 2017), ground water contamination detection (Yochim et al., 2013), subsurface water profiling (Doolittle et al., 2006; Mahmoudzadeh et al., 2012), soil and conductivity studies (Rohini and Singh, 2004; Shamal et al., 2016; Wang et al., 2017), near surface soil characterisation (Islam and Chik, 2013), and so on. Hence, many previous researchers have focussed on developing correlations for electrical resistivity of various soils (Archie, 1942; McCarter, 1984; Fukue et al., 1999; Shah and Singh, 2005; Kibria and Hossain, 2012; Yan et al., 2012; Pandey et al., 2015).

The parameters affecting the conductivity of various soil types, differ significantly. For the coarse fraction like sand, the conductivity depends on interconnected voids, conductivity of interstitial fluid, state of compaction and granular skeleton. However, for clayey soils, the conductivity is governed by pore fluid conductivity as well as surface charge of the clay mineral (Mitchell and Soga, 2005). Consequently, the bentonite content of soil is known to have a significant impact on its electrical resistivity (Abu-Hassanein et al., 1996; Kumar and Yong, 2002; Kibria and Hossain, 2014). Although many researchers have previously developed the relationship between the geotechnical properties of soil and its electrical resistivity, there are a limited number of studies to analyse the effect of bentonite content of soil on its resistivity (Shah and Singh, 2005). Furthermore, it is well-known that both water content and the degree of compaction are essential criteria to determine resistivity of soil (McCarter, 1984; Kalinski and Kelly, 1993). Hence, there is a significant scope for the development of correlations for the resistivity of soils which incorporate the effect of the state of compaction on the electrical resistivity of sand-bentonite liner materials. Therefore, the purpose of this study is to characterize the electrical resistivity of the bentonite and sand-bentonite soil liners, so that later, this property could be measured to estimate soil contamination.

In most research works carried out in the past on investigation of electrical resistivity of soils, the dry unit weight γ_d of soils have been kept constant and the effect of changing water content on the resistivity has been investigated (McCarter, 1984; Abu-Hassanein et al., 1996; Kibria and Hossain, 2012; Bai et al., 2013; Kibria and Hossain, 2014). In this research, the unit weight γ_d has been varied such that at each water content, the maximum compaction is achieved. The motivation behind this is to replicate actual lining materials, as used in practice. Furthermore, the effect of bentonite content of soil and its state of compaction have been scrutinized for Australian soils. The focus in this research is to investigate the variation of resistivity as a geophysical parameter with the state of compaction, because the soil in field projects related to roads, embankments, foundations, and other geotechnical structures in civil engineering are regularly compacted. Therefore, the developed figures may work as the design charts for practising geotechnical/civil engineers. The results as presented, are highly useful to predict the densification of liner based on the non-destructive test that uses the resistivity measurement. This new research development can help avoid disturbing the compacted liner material at the landfill site, and hence, prevent any disturbance that can increase the infiltration of landfill leachate.

The results obtained from this study will provide a baseline for the detection of liner leakage for application in Australia as well as in other parts of the world. In addition, newly developed correlations have also been proposed, aiming at their application in liquid impoundment facilities, waste storage and handling facilities, contamination detection, liner leak detection, development of sensors, soil and corrosion studies, and so on.

2. Materials and methods

Sand obtained from quarries around Perth, Western Australia (WA) is used for the experiments. Table 1 gives its various physical properties. Fig. 1 shows the particle-size distribution curves of sand and bentonite. As per the Unified Soil Classification System (USCS), the sand is classified as poorly graded (SP) sand, which is a good representation of soil in WA.

The bentonite specimen used in this study is powdered sodium bentonite, procured from Ebenezer mine site in Queensland, Australia. Its various properties are listed in Table 2, and is classified as the highly plastic clay, also called the fat clay (CH) as per the Unified Soil Classification System (USCS). Table 3 shows the composition of the tap water which has been used in this study. The tap water has been used as a representation of the groundwater.

A total of five soil mixes were prepared for the study by mixing different amounts of oven-dried sand and bentonite, such that the bentonite in the soil mixtures was varied from 20 to 100% by weight. Standard Proctor compaction test was conducted for all soil mixtures, in accordance to the Australian Standard AS 1289.5.1.1–2003 (Standard Australia, 2003). It is an experimental method to determine the optimum water content at which a soil becomes most dense and achieves its maximum dry unit weight. The test is performed by compacting a soil at known water content into a

Table 1
Physical properties of sand.

Property	Value	Unit
Specific gravity, G_s	2.68	Dimensionless
Coefficient of uniformity, C_u	2.27	Dimensionless
Coefficient of curvature, C_c	1.22	Dimensionless
Effective size, D_{10}	0.15	mm
Minimum dry unit weight, $\gamma_{d\min}$	14.02	kN/m^3
Maximum dry unit weight, $\gamma_{d\max}$	15.56	kN/m^3
Soil classification as per USCS (Unified Soil Classification System)	Poorly graded sand (SP)	Dimensionless