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Investigation of degree of saturation in landfill liners using electrical resistivity imaging

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ABSTRACT

During construction of compacted clay liners and evapotranspiration (ET) covers, quality control involves laboratory and field tests in individual lifts. However, the available methods may be inadequate to determine non-uniform compaction conditions, poor bonding of lifts, and/or variable soil composition. Moreover, the applicability of the available methods is restricted, in many instances, when spatial variability of the subsurface is expected. Resistivity Imaging (RI) is a geophysical method employed to investigate a large area in a rapid and non-destructive way. High resistivity of clay liner soil is an indication of a low degree of saturation, high air-filled voids, and poor lift bonding. To utilize RI as a quality control tool in a landfill liner, it is important to determine the saturation condition of the compacted soils because compaction and permeability of liner soil are functions of degrees of saturation. The objective of the present study is to evaluate the degree of saturation of a municipal solid waste (MSW) landfill liner, using RI. Electrical resistivity tests were performed in the laboratory, at varied moisture contents and dry unit weights, on four types of soil samples, i.e., highly plastic clay (CH), low plastic clay (CL), Ca-bentonite, and kaolinite. According to the experimental results, electrical resistivity of the specimens decreased as much as 15.3 times of initial value with increase in the degrees of saturation from 23% to 100%. In addition, cation exchange capacity (CEC) substantially affected resistivity. A multiple linear regression (MLR) model was developed to correlate electrical resistivity with degree of saturation and CEC using experimental results. Additionally, RI tests were conducted on compacted clay liners to determine the degrees of saturation, and predicted degrees of saturation were compared with the in-situ density tests. The study results indicated that the developed model can be utilized for liner soils having CEC, resistivity and degrees of saturation between 13.3 and 79 cmol +/kg, and 2.6 and 504.3 Ohm m, and 21.8% to 100%; respectively.

1. Introduction

Compacted clay soils are widely used to line waste impoundments and to close the waste disposal unit. During construction of bottom liners, stringent quality controls are recommended to ensure low hydraulic conductivity ($K_s \leqslant 1 \times 10^{-7}$ cm/s). Therefore, it is important to identify the appropriate compaction condition of soils to restrict water intrusion through compacted clay liners. Daniel and Benson (1990) proposed an acceptable zone in the moisture density curve of liner soils, which encompasses low hydraulic conductivity criterion. Although it is important to consider the acceptable zone during compaction of liners, the proposed moisture–density zone can be modified to take into consideration shear strength, shrink-swell criteria, and the construction practices of a given area. Additionally, Benson et al. (1999) performed a study to evaluate the importance of compaction parameters, i.e., molding water content and dry density, to the construction of clay liners. According to the study, an increase in the degree of saturation in the soils caused a reduction in hydraulic conductivity of clay liners, resulting in their being under the acceptable zone of moisture-density curve.

The evaluation of change in the degree of saturation in vertical and horizontal directions is also important for the effective performance of an evapotranspiration (ET) cover. An increase in saturation emphasizes that the cover system is approaching its storage capacity. Specifically, when the ET cover consists of a capillary barrier, saturated fine soil provides an indication of the potential percolation (Hakonson, 1997).

Because of time and cost constraints, a detailed investigation of non-uniform compaction conditions, poor bonding of lifts, and/or variable soil composition in clay liners, final covers, and ET covers

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is often not possible, using the available in-situ and laboratory methods. Moreover, the applicability of the available methods is restricted, in many instances, when spatial variability of the subsurface is expected.

Resistivity Imaging (RI) is a geophysical method employed to investigate a large area in a rapid and non-destructive way. This method can provide a continuous image of subsurface in both vertical and horizontal directions. RI method utilizes electrical resistivity responses of soils which are functions of degree of saturation, clay content, pore water, and mineralogical content. Typically, high resistivity of clay liner soils is an indication of a low degree of saturation, high air-filled voids, and poor lift bonding (Kalinski and Kelly, 1994). Kalinski (1992) conducted electrical resistivity tests in compacted liner of Lincoln landfill using Wenner configuration. The liner soil consisted of high plasticity clay (CH), low plasticity clay (CL), and clayey silt (ML–CL). The study results indicated that the resistances of liner soils were in between 4.0 and 5.4 Ohm. Therefore, RI method can be used as a tool for construction quality control in clay liners of landfill.

The application of electrical resistivity to evaluate moisture and density is documented in several studies. McCarter (1984) evaluated the effect of air-void ratio in soil resistivity on Cheshire and London clays. The results of the study indicated that the degree of saturation is an important factor in resistivity variation. Abu-Hassanein et al. (1996) performed a comprehensive study on the effects of molding water content and compactive efforts in soil resistivity. It was observed that the resistivity was high, when soil was compacted at dry optimum, and low, when compacted at wet optimum. Moreover, resistivity was sensitive to molding water content below optimum condition. On the other hand, resistivity was almost independent of molding water content at wet of optimum.

In addition, electrical resistivity can provide useful information about moisture distribution, presence of voids, and heterogeneity of the final cover. Genelle et al. (2011) conducted a study using Resistivity Imaging (RI) and self-potential (SP) methods to determine water recharge in the final cover. The study results indicated that RI was able to map cracks in the final cover. Carpenter et al. (1991) researched the fracture and erosion of landfill covers, using electrical resistivity and seismic refraction. The results showed that the azimuthal resistivity was able to identify deep cover cracks, which required remediation to avoid infiltration of moisture and emission of landfill gases.

It is evident that degree of saturation provides information about the compaction condition and hydraulic conductivity of clay liners. Additionally, the percolation condition in an ET cover is associated with the moisture and storage capacity, and these parameters are also related to the degree of saturation. Therefore, quantification of degree of saturation is required to utilize RI as a quality control tool in the construction of bottom liners and final covers of landfills. However, very limited studies have been conducted to determine the saturation condition of landfill liners using RI. The objective of the present study is to evaluate the degree of saturation of a municipal solid waste (MSW) landfill liner, using RI. Laboratory investigations were conducted to identify the effect of the degree of saturation and cation exchange capacity (CEC) on resistivity. Based on the experimental results, a model was developed and utilized to quantify the degree of saturation from RI in compacted clay liners of the City of Denton, Texas landfill.

2. Laboratory investigation

2.1. Characterization of soil samples

A total of four types of soil samples were utilized for investigating the geotechnical properties affecting electrical resistivity and developing a statistical model for compacted clays. The soil specimens included (a) highly plastic clay (CH), (b) low plasticity clay (CL), (c) Ca-bentonite, and (d) kaolinite. Ca-bentonite and kaolinite minerals were used to determine the resistivity responses at two specific mineralogical conditions. The CH and CL specimens were collected from a slope along highway Loop 12 near the Union Pacific Railroad (UPRR) in Dallas, Texas. The samples were collected at a specific period of time to avoid temporal variability. Additionally, artificial soil samples were prepared using Ca-bentonite and fine sands at different weight percentages, and were used to validate the statistical model. A summary of artificial soils used for model validation is presented in Table 1.

Table 1
Artificial soil specimens utilized in the study.

Ca-bentonite percentages by weight	Sand percentages by weight
80	20
60	40
40	60
20	80

An experimental program was developed to determine grain size distribution, Atterberg limits, specific gravity, and CEC of the soil samples according to ASTM D422, ASTM D431, ASTM D854, and ASTM D7503, respectively. Grain size distribution of the specimens indicated that the percent passing through a #200 sieve (0.075 mm) was more than 90% in Ca-bentonite, kaolinite, and CH specimens. The observed liquid limits (LL) and plasticity indices (PI) of the soils ranged from 22 to 107 and 7 to 55, respectively. Test results suggested that the CEC of soil specimens ranged from 13.3 to 79.0 cmol+/kg. In addition, LL, PI, and CEC were high in artificial samples those contained high percentages of Ca-bentonite fractions. Geotechnical properties of the test specimens are presented in Table 2.

2.2. Electrical resistivity tests

Soil resistivity tests were performed at varied moisture contents and dry unit weights. The soil samples were compacted in the resistivity box at a predetermined moisture content and dry unit weight, and electrical resistivity of the soils was measured with a four-electrode configuration, using Super Sting IP equipment. A current was directed to the soil through two current electrodes, and the voltage drop was determined between two points within the specimen. During resistivity tests, moisture contents and dry unit weights varied from 10% to 40% and 11.8 to 14.9 kN/m^3, respectively. Moreover, temperatures of test conditions ranged from 3.0 to 35 °C in each case, (i.e., for a specific soil type, moisture content, and dry unit weight). Thereafter, the soil resistivity at each temperature was corrected to 15.5 °C, according to the ASTM G187-05 standard method and the average resistivity

Table 2
Summary of geotechnical properties of test specimens.

Soil specimens	LL	PI	Gs	% Passing #200 sieve (0.075 mm)	CEC (cmol+/kg)
Ca-bentonite	107	55	2.42	94	79.0
Kaolinite	61	24	2.68	100	13.3
Low plasticity clay (CL)	32	15	2.67	65	19.0
Highly plastic clay (CH)	53	30	2.65	92	41.0
80% Ca-bentonite–20% sand	80	43	2.44	75	63.5
60% Ca-bentonite–40% sand	55	26	2.63	56	45.5
40% Ca-bentonite–60% sand	40	18	2.56	38	38.1
20% Ca-bentonite–80% sand	22	7	2.69	19	27.9