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Detection of leachate contamination in Perth landfill base soil using electrical resistivity technique

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ABSTRACT
The electrical resistivity of landfill base soil changes when leachate infiltrates into the soil, due to leakage through the liner. This paper presents the results of an investigation into the effects of fluid (water and/or leachate) content of soil, and type of leachate on the electrical resistivity of Perth landfill base soil. The experimental apparatus used for the resistivity measurements was fabricated as per Australian standard AS 1289.4.4.1-1997. Three leachates were procured for the experimentation. The infiltrating fluid consisted of a mixture of water and leachates in varying concentration, to simulate the base soil contamination in field situations. The test results showed that the electrical resistivity of the Perth sandy soil decreased rapidly when the fluid content increased. The resistivity of the soil was found to decrease significantly with increase in the leachate content in the fluid. However, the rate of decrease of resistivity became less significant for fluid contents over 9%, irrespective of the leachate content in the fluid. Additionally, it was observed that the rate of decrease of resistivity was almost independent of the type of leachate for leachate contents more than 20%. The resistivity-leachate content curves for each of the leachates demonstrated a point of inflection at leachate content of 30%. The results indicate that the changes to the resistivity arising from changes to the fluid content are more significant than the effect of varying the leachate content or type within any specific mixture of water and leachate. Newly developed correlations between the resistivity and the geotechnical properties of the soil infiltrated with leachates, have also been presented.

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Introduction

The safe storage and the disposal of industrial and domestic wastes are among the most challenging problems that are being faced by the global community in recent times. The impact that these wastes have on the environment, and on human health, has become a matter of growing concern (Tuxen, Albrechtsen, and Bjerg 2006; Canton et al. 2010). Engineering solutions, such as liner containment systems, have been proposed to manage the leachate containment problem appropriately. When employing a liner containment system, the potential threat posed by each category of waste determines the specific type of liner system best suited to a particular site (Shah 2000). Not surprisingly, the long-term integrity of the liner materials is critical (Daniel 1984), but as the liner must endure aggressive hydraulic, mechanical, thermal and chemical environments, it is not possible to ascertain the performance efficiency over its intended design life in advance (Rowe et al. 2004; Oh et al. 2008). The effective containment of leachates in waste storage systems, such as landfills, leachate collection ponds, tailing dams, sump wells, etc., necessitates vigilant monitoring and prompt repair of leaks in the liner system once it has been detected (Harrop-Williams 1985). Although there are several established techniques for detecting leakage through the liners (Okoye, Cotton, and O'Meara 1995; Wilson, Everett, and Cullen 1995; Kaya and Fang 1997), the use of an electrical resistivity method could assist in the timely detection of contaminant leakage in a cost-effective manner (Oh et al. 2008). This proposed method is based on the well-established fact that the electrical resistivity of soils and other geomaterials is much higher than the electrical resistivity of water, leachates, or any liquid effluents that may permeate the landfill foundation material (Rhoades, Raats, and Prather 1976; McCarter 1984; Mccarter and Desmazes 1997; Yoon and Park 2001; AS/NZS 2007; Munoz-Castelblanco et al. 2012; Yan, Miao, and Cui 2012; Kuranchie et al. 2014; Pandey, Shukla, and Habibi 2015; Kolay, Burra, and Kumar 2016). The very high electrical resistivity of typical soils (Fukue et al. 1999; Munoz-Castelblanco et al. 2012) can be altered by the addition of even traces of a contaminant (Darayan et al. 1998; Yoon and Park 2001). The presence of such small amounts of a given contaminant can be readily detected using the electrical resistivity method.

Additionally, it has been determined that the geotechnical properties of a soil exhibit a close relationship with the electrical resistivity values across a range of conditions (Archie 1942; Gupta and Hanks 1972; Kalinski and Kelly 1993; Pandey, Shukla, and Habibi 2015; Kolay, Burra, and Kumar 2016). Gaining an understanding of the relationship between the geotechnical and electrical properties of the common soil types has many useful

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Table 1. Physical properties of Perth sandy soil.

Properties	Values
Specific gravity of soil solids, G_s	2.68
Coefficient of uniformity, C_u	2.27
Coefficient of curvature, C_c	1.22
Effective size, D_{10} (mm)	0.15
Minimum dry unit weight, γ_{dmin} (kN/m^3)	14.02
Maximum dry unit weight, γ_{dmax} (kN/m^3)	15.56
Soil classification as per USCS (Unified Soil Classification System)	Poorly graded sand (SP)

applications in civil and environmental engineering, such as predicting electrical resistivity from known geotechnical parameters (Kalinski and Kelly 1993), contamination detection, corrosion studies (BSI 1990), anomaly detection (Panthulu, Krishnaiah, and Shirke 2001), soil salinity studies (Gupta and Hanks 1972; Rhoades et al. 1977; Adam et al. 2012) and agricultural applications (Samouëlian et al. 2005). Hence, many previous researchers have investigated the relationship between the various geotechnical parameters of a given soil type and the corresponding electrical resistivity. Archie (1942), Fukue et al. (1999), and Kalinski and Kelly (1993) have developed correlations between the electrical resistivity of soils and their geotechnical parameters. These correlations can be used for the primary prediction of resistivity when the geotechnical properties of soil are known, and vice versa. Pandey, Shukla, and Habibi (2015) investigated the effect of various electrical factors pertaining to resistivity tests, specifically AC-input voltage and frequency; and those controlling the soil characteristics, specifically water content and relative density of the soil. Furthermore, they have presented newly developed correlations for the electrical resistivity of Perth sandy soil. In the study by Pandey, Shukla, and Habibi (2015), the electrical resistivity of Perth soil was found to be independent of the electrode material, the input voltage and the frequency of the applied current. The relative density of the soil was found to have only a limited effect on the resistivity. In a similar manner, correlations can be developed between the electrical resistivity and geotechnical properties of a soil infiltrated by leachates.

Although several researchers have focused on changes to the electrical properties of certain soils while attempting to detect the presence of contamination (Darayan et al. 1998; Yoon and Park 2001); the relationship between changes in soil resistivity and gradual increases in the amount of contaminating leachate is largely unknown, Perth sandy soil being a case in point. This research paper presents the effect on the electrical resistivity of Perth soil specimens, produced by gradually changing the leachate content within the infiltrating fluid (water-leachate mixture). As the Perth metropolitan area is mainly composed of sandy soil, the possibility of detecting contamination by the use of the electrical resistivity method is an attractive proposition. Hence, the study is designed to provide an insight into the behaviour of Perth landfill base materials due to leachate contamination. In addition, the purpose of the study is to develop the knowledge, which can help to check contamination on-site using the electrical resistivity measurements of landfill base soil through any suitable device.

New correlations have also been developed between the resistivity and the geotechnical properties of the soil, infiltrated with leachates. The results obtained by these studies can find application in contamination detection, and for the development of sensors for detecting and locating leakages.

Materials and methods

Sandy soil

Perth sandy soil was used for this research. It is obtained from quarries and is widely used as landfill foundation material, and for other construction purposes in Western Australia (WA). The soil was classified as a poorly graded sand (SP) as per the Unified Soil Classification System (USCS) (ASTM 2009). Table 1 lists the various properties and Figure 1 shows the particle-size distribution curve for the soil. Figure 2 provides a scanning electron microscopy (SEM) image of the Perth soil, while Figure 3 shows the results of a qualitative analysis of the sandy soil, obtained using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM/EDS). It may be noted that CKa, Oka, AlKa, and SiKa are standard notations that refer to the characteristic K_α peaks of carbon, oxygen, aluminium and silicon, respectively.

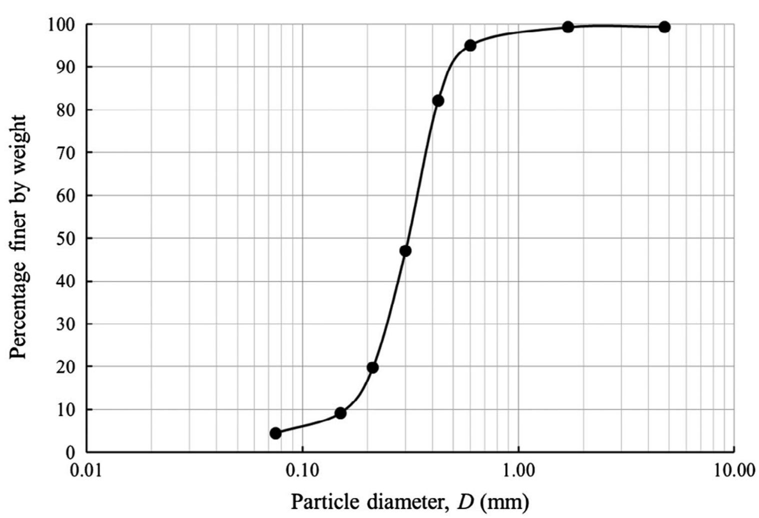

Figure 1. Particle-size distribution curve for Perth sandy soil.

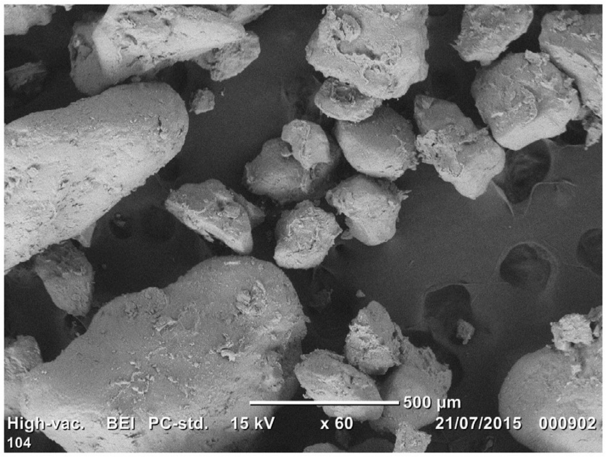

Figure 2. Scanning electron microscopy (SEM) images of Perth sandy soil.

Pore fluids

Several fluids, as the water-leachate mixture, were mixed with the Perth sandy soil to prepare the test specimens. Tap water was used to represent groundwater for this study. The water quality data for tap water as provided by the Water Corporation, Western Australia (WA) is listed in Table 2.

Three types of leachates were used as liquid effluents for the experimentation. Leachate #1 was obtained from the Tamala Park Landfill, operating under the Mindarie Regional Council (MRC), WA. It is the effluent obtained from the landfill leachate collection system. Leachates #2 (iron ore liquor) and #3 (NUA liquor) were obtained from the Iluka Resources, Capel Valley, WA. The company is involved in mineral sand processing. The details of the composition of Leachate #1, #2 and #3 are given in Table 3.

Sample preparation

Varying percentages of Leachate #1, Leachate #2 and Leachate #3 (0% to 100%), denoted by p_l, were mixed with tap water and these mixtures were used as the pore fluids. The leachate content p_l in the fluid mixture was calculted using the leachate volume V_l and the total fluid volume V_f, as explained below:

$$p_l = \frac{V_l}{V_f} \tag{1}$$

Because the pore fluid within the soil mass throughout this study comprised of various proportions of Leachates #1, #2 and #3 along with tap water; the term fluid content (w) of contaminated soil has been used instead of water content in this paper, as defined below:

$$w = \frac{W_f}{W_s} \tag{2}$$

where W_f is the weight of fluid within the soil mass and W_s is the dry weight of soil mass.

The soil sample was oven-dried at 110 °C overnight before the pore fluid was added to contaminate the soil. After drying, a measured amount of oven-dried soil was then mixed with a specific amount of fluid, to achieve the desired water/fluid content.

For each fluid mixture (tap water + leachate), the fluid content w of the soil was increased progressively from 4% to 16% and the corresponding electrical resistivity values were determined by using the experimetal technique as described in the following section. The lower limit of 4% fluid content was selected based on previous research, which indicated that dry soils and soils with a very small fluid content exhibit extremely high resistivity values, and these high values are often beyond the range of the measuring instrument (Gupta and Hanks 1972; Rhoades, Raats, and Prather 1976; McCarter 1984; Kalinski and Kelly 1993; AS/NZS 2007; Munoz-Castelblanco et al. 2012; Yan, Miao, and Cui 2012; Kuranchie et al. 2014; Pandey, Shukla, and Habibi 2015; Kolay, Burra, and Kumar 2016). At a fluid content of 20%, near saturation conditions are attained.

In addition, it has been previously observed that the relative density D_r exhibits only a limited effect on the resistivity when

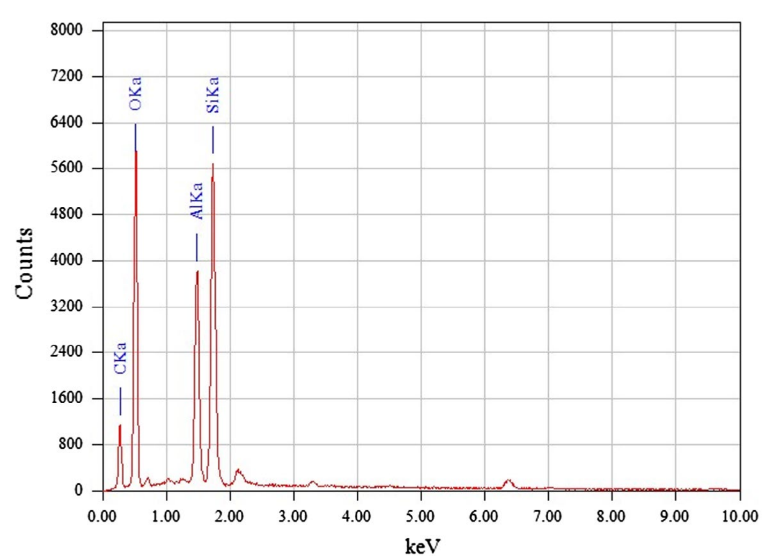

Figure 3. Qualitative analysis of the sandy soil obtained using scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDS).

Table 2. Water quality data for tap water (as per Water Corporation, WA).

Properties	Unit	Values
Alkalinity as $CaCO_3$	mg/L	83
Alkalinity as HCO_3	mg/L	101
Aluminium acid soluble	mg/L	0.045
Aluminium unfiltered	mg/L	0.045
Calcium	mg/L	28
Chloride	mg/L	185
Chlorine-free residual	mg/L	0.49
Conductivity (at 25 °C)	mS/m	83
Filterable organic carbon	mg/L	1.8
Hardness as $CaCO_3$	mg/L	100
Iron unfiltered	mg/L	0.02
Magnesium	mg/L	7.8
Manganese unfiltered	mg/L	0.002
Nitrate plus nitrite as N	mg/L	0.45
pH	pH Units	7.86
Potassium	mg/L	7
Silicon as SiO_2	mg/L	17
Sodium	mg/L	110
Sulphate	mg/L	29
Total filterable solids	mg/L	496
True colour	HU	<1
Turbidity	NTU	<0.1

Table 3. Composition of Leachates #1, #2 and #3.

Properties	Unit	Leachate #1	Leachate #2	Leachate #3
Ammonia as N	mg/L	2200.00	2194.04	34.58
Bicarbonate HCO_3 as $CaCO_3$	mg/L	11396.00	14.50	9.20
Calcium	mg/L	59.00	111.50	677.23
Carbonate CO_3^{2-} as $CaCO_3$	mg/L	<5	3.00	62.40
Chloride	mg/L	2700.00	6811.67	515.45
Electrical conductivity	µS/cm	26000.00	19008.67	3843.07
Hardness as $CaCO_3$	mg/L	410.00	500.00	2100.00
Hydroxide OH^- as $CaCO_3$	mg/L	<5	3.00	41.60
Magnesium	mg/L	63.00	42.40	18.42
Nitrate as N	mg/L	<0.5	3.44	3.24
pH	pH units	7.90	7.90	10.24
Potassium	mg/L	1400.00	59.60	26.33
Sodium	mg/L	2000.00	180.00	225.15
Sulphate	mg/L	26.00	226.63	1565.22
Total alkalinity as $CaCO_3$	mg/L	11396.00	14.50	108.00
Total organic carbon	mg/L	1890.00	–	–

Note: Courtesy of the Tamala Park landfill, Mindarie Regional Council (MRC), WA and Iluka Resources, Capel Valley, WA.

compared to the water content (Pandey, Shukla, and Habibi 2015). Hence, D_r was fixed at 50% that corresponds to the dry unit weight, $\gamma_d = 14.72$ kN/m^3, while the fluid content of the soil was varied. The total unit weight γ of soil mixed with fluid was then calculated corresponding to the relative density D_r of 50%, and a specific fluid content w, using the folowing relationship:

$$\gamma = \gamma_d(1 + w) \quad (3)$$

The weight of soil-fluid mixture to be filled in the resistivity soil box was then determined by multiplying the calculated value of γ and the internal volume of the box. The weighed soil specimen was divided into three parts, and the soil box was filled in layer by layer in order to maintain homogeneity. Three levels were marked on the box to ensure that each soil layer supplied approximately one-third of the box's volume. Gentle blows with a small tool were given to compact the soil down to the correct level for each of the three lifts.

Experimental technique

The electrical resistivity of the soil with different contaminated conditions was determined by conducting tests in accordance with the Australian standard AS 1289.4.4.1-1997: determination of the electrical resistivity of a soil - method for sands and granular materials (Standards Australia AS: 1289.4.4.1 1997).

Experimental set-up

As per AS 1289.4.4.1-1997 (1997), a resistivity box (as shown in Figure 4) was fabricated by using 10-mm-thick perspex sheets and was then fitted with brass electrodes. The dimensions of the box were 200-mm internal length, 40-mm internal width and 30-mm internal depth.

The resistivity box was fitted with two current plate electrodes, C_1 and C_2. The dimensions of each of the plate electrodes were 40 mm width, 30 mm depth and 10 mm thickness. Two voltage-potential measuring pins, P_1 and P_2, were also fitted in the box as shown in Figure 4. The distance between the axes of pins P_1 and P_2 was 120 mm and their diameter was 3 mm.

An AC-input current was chosen for use in the study, as the AC current reduces polarisation effects (Sachs and Spiegler 1964; McCarter 1984; Yan, Miao, and Cui 2012). The AEMC 6471 ground resistance testing machine was used for the experimentation. This equipment can provide different AC-input voltages

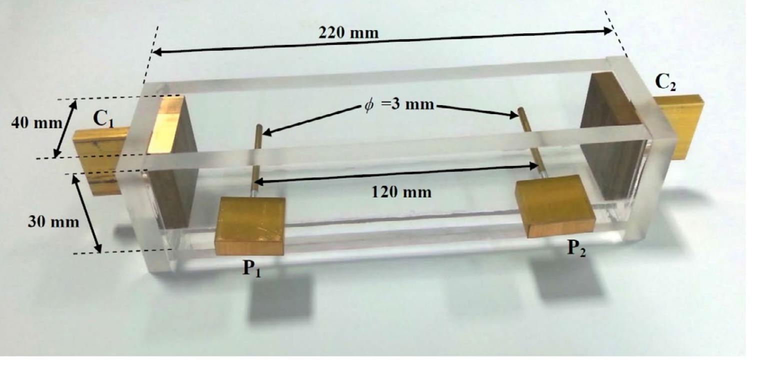

Figure 4. Resistivity box fabricated for the study as per AS 1289.4.4.1-1997.

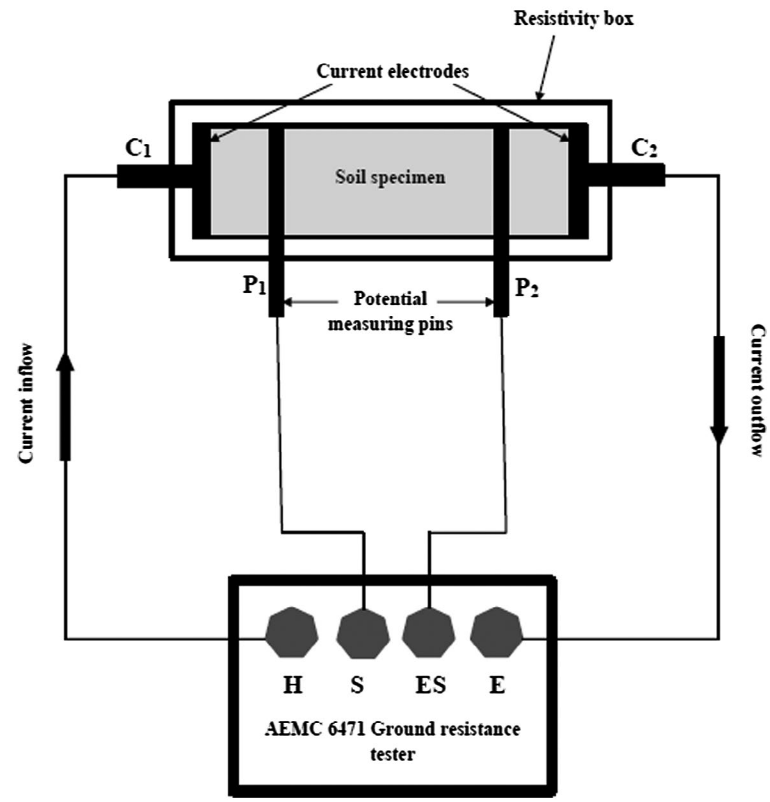

Figure 5. Schematic diagram of the experimental set-up used for the measurement of electrical resistivity as per AS 1289.4.4.1-1997.

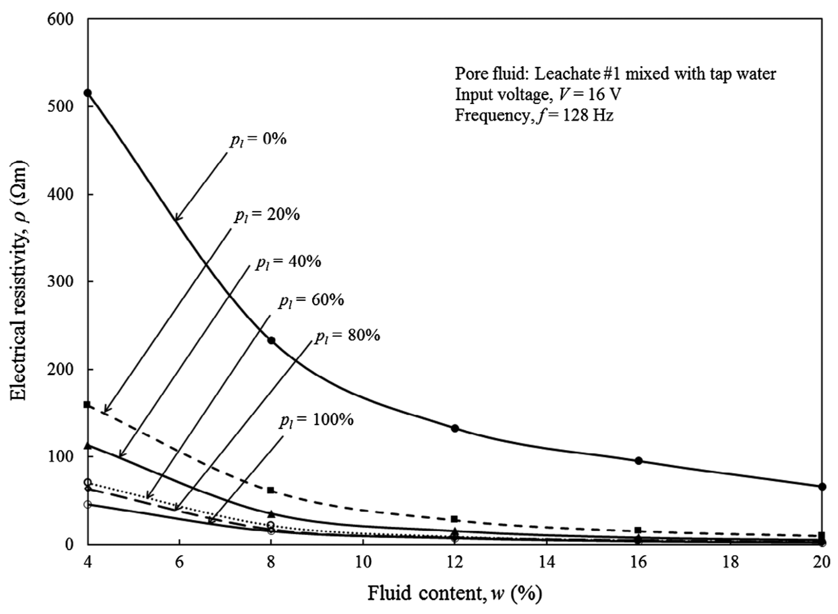

Figure 6a. Variation of electrical resistivity with fluid content for Leachate #1 and tap water mixture used as a pore fluid.

(16 and 32 V) and AC-input frequencies (55, 92, 110, 119, 128 and 550 Hz) for testing.

The past studies have shown that AC-input voltage and frequency have a negligible effect on the electrical resistivity of sandy soils. Hence, typical values of AC-input voltage of 16 V and frequency of 128 Hz have been selected in the present work. Similar values have also been considered in other research work (Mccarter and Desmazes 1997; Yan, Miao, and Cui 2012; Pandey, Shukla, and Habibi 2015).

Test procedure

Figure 5 shows the schematic diagram of the system used to measure the electrical resistivity $\rho(\Omega\text{m})$ of the soil sample. The resistivity testing box filled with a soil specimen, and the AEMC ground resistance testing machine were connected as shown in the figure. The current plate electrodes C_1 and C_2 were connected to the ground resistance tester's current knobs H and E, respectively. The potential measuring pins P_1 and P_2 were connected to the potential knobs S and ES, respectively.

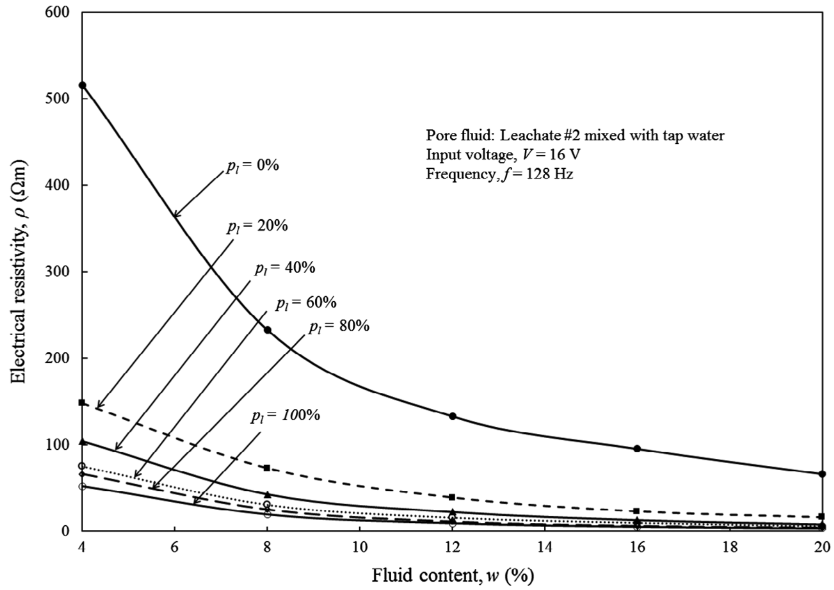

Figure 6b. Variation of electrical resistivity with fluid content for Leachate #2 and tap water mixture used as a pore fluid.

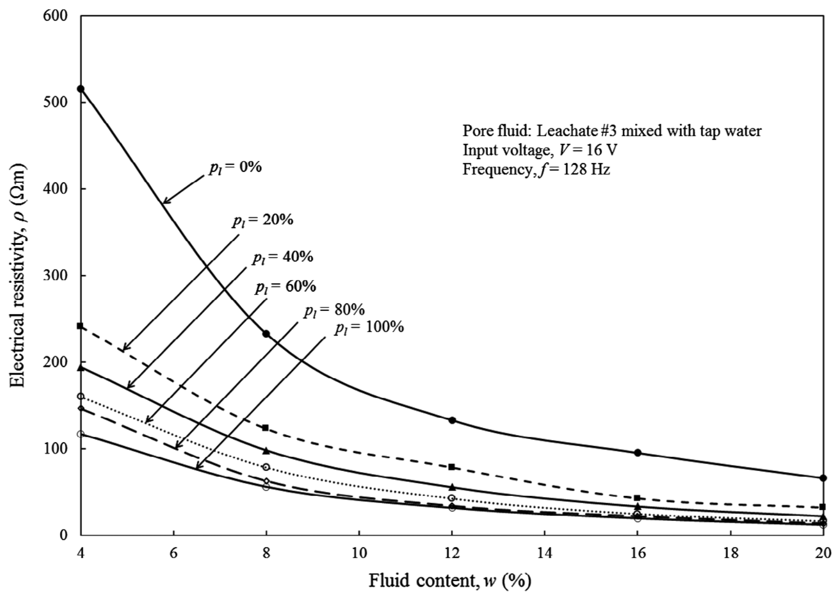

Figure 6c. Variation of electrical resistivity with fluid content for Leachate #3 and tap water mixture used as a pore fluid.

Electric current was passed through the soil specimen via the outer plate electrodes. The potential drop across P_1 and P_2 was determined to calculate the resistance $R(\Omega)$ of the specimen. Due to the geometry of the resistivity box used in this test, the resistivity of the soil specimen can be calculated as follows:

$$\rho = \frac{R}{100} \tag{4}$$

The electrical resistivity readings were recorded for various values of fluid content w, leachate content p_l and type, and the data obtained were then analyzed.

The metal electrodes were cleaned prior to each set of tests to eliminate any electrodeposition (Bicelli et al. 2008; Pandey, Shukla, and Habibi 2015). Controlling the soil temperature is important, as the temperature changes affect the electrical resistivity (AS/NZS 2007). To avoid any temperature induced variation in soil resistivity (Grellier et al. 2006), the room temperature was maintained at 20 °C (Kalinski and Kelly 1993) during the tests.

Results and discussion

Figures 6a–6c give the variation of the electrical resistivity of the soil with an increase in the fluid content. It is observed that for any fluid content, the resistivity exhibits the highest values when the leachate content in the fluid mixture (p_l) is 0%, that is, when only the tap water is added to the soil. Furthermore, it can be noticed from Figures 6a–6c that as the fluid content increases, the change in resistivity caused by increasing p_l, is reduced.

The resistivity of soil mixed with tap water alone is far greater than when a leachate is added to the pore fluid. This observation was expected as the tap water contains significantly less

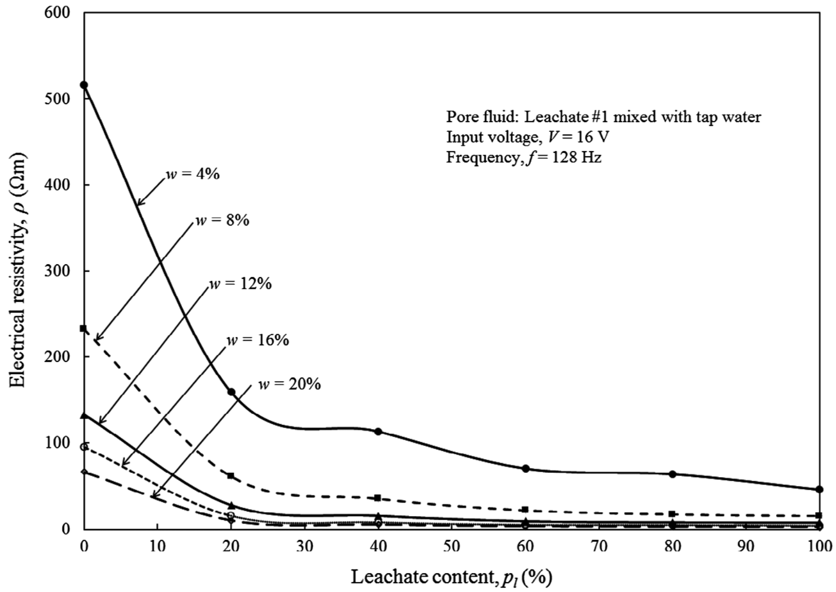

Figure 7a. Variation of electrical resistivity with leachate content using Leachate #1.

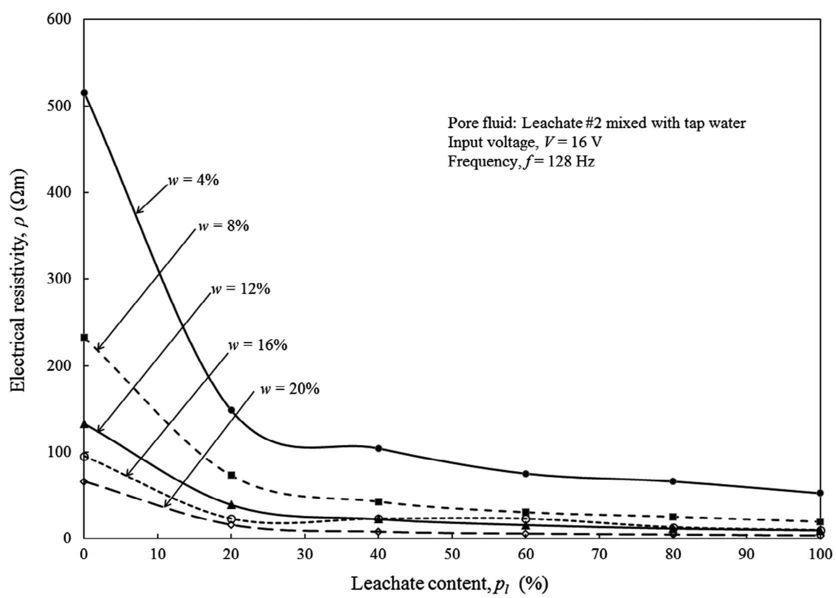

Figure 7b. Variation of electrical resistivity with leachate content using Leachate #2.

electrolytes (Table 2) in comparison to the three leachates (Table 3). In addition, this reinforces the understanding that when liquid effluents permeate a geomaterial, they alter the electrical properties of that geomaterial. Hence, by detecting these changes to the electrical properties, contamination in the soil can be effectively determined. This conclusion is consistent with the findings from other studies such as Darayan et al. (1998), and Yoon and Park (2001).

It is further observed from Figures 6a–6c that an increase in the fluid content w results in a subsequent decrease in the resistivity. The resistivity ρ shows a rapid decrease initially, because of increases in w. However, for w greater than 9%, the change in resistivity becomes more gradual. For example, from the curve of $p_l = 20\%$ (Figure 6a); the rate of decrease in resistivity for w increasing in value from 6% to 8%, is observed to be 21.86 Ωm. The rate of decrease of resistivity becomes 6.09 Ωm for w increasing in value from 10% to 12%. Similar observations have been made in the past study by Kolay, Burra, and Kumar (2016). This study investigated the effect of salt and nonaqueous-phase liquid (NAPL) on the electrical resistivity of various soil mixtures, and reported a decreasing trend of resistivity of soil with increase in its water content.

These observations for the electrical resistivity of soil are more pronounced at lower p_l. Furthermore, it can be noted from the figures that for all the three leachates, the turning point of the curve is nearly the same, at a fluid content of 9%. It can also be seen from the Figures 6a–6c that for w greater than 16%, when the soil is at near saturation conditions, the resistivity becomes nearly constant.

Figures 7a–7c depict the variation of the electrical resistivity with increasing leachate content (p_l). The shapes of the curves

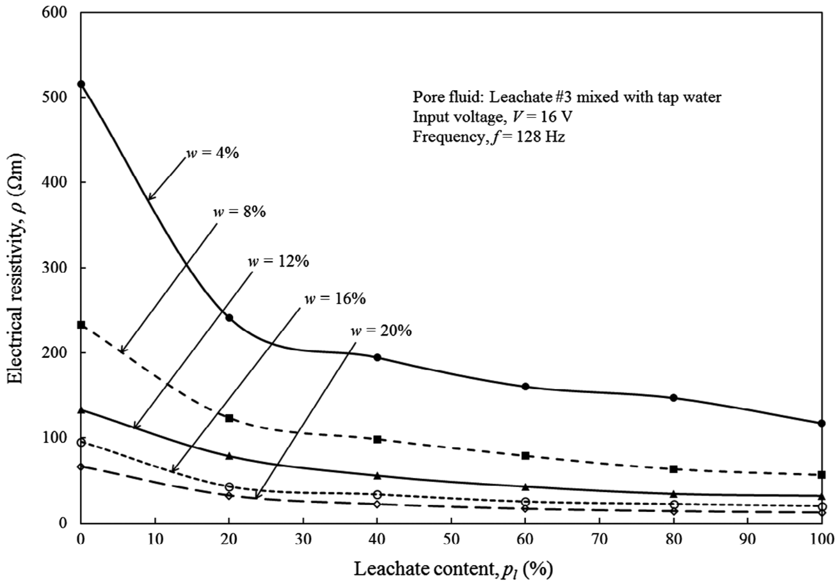

Figure 7c. Variation of electrical resistivity with leachate content using Leachate #3.

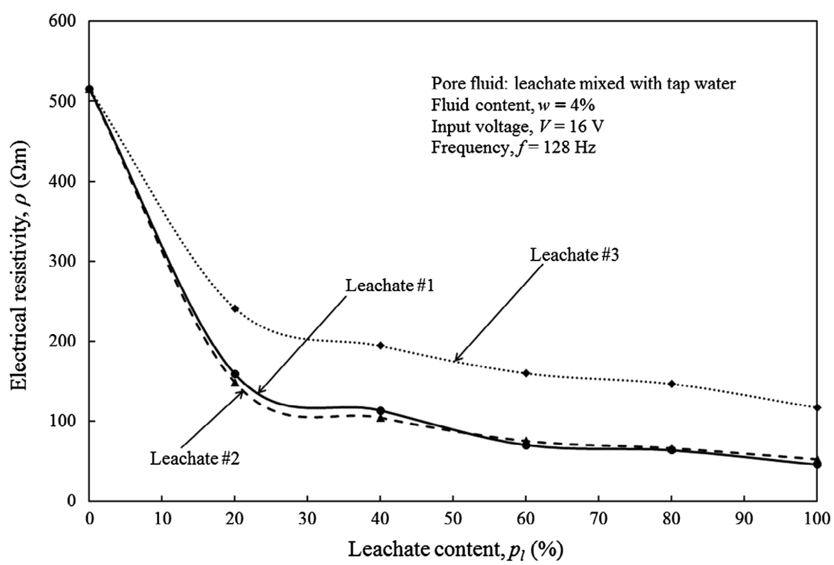

Figure 8a. Comparison of Leachate #1, Leachate #2 and Leachate #3 at fluid content of 4%.

are similar for each of the three leachates used in this study. The resistivity shows a rapid decrease with an increase in p_l. The rate of decrease is significantly reduced for values of p_l greater than 20%. Additionally, for Leachates #1, #2 and #3, it is observed that each curve indicates a point of inflection where $p_l = 30\%$.

When the leachate content exceeds 20%, only a minor decrease in resistivity is observed, irrespective of the fluid content *w* of the soil. Furthermore, at higher values of *w* (greater than 8%), the value of the resistivity is found to become nearly constant. Consequently, it can be inferred that at higher fluid contents, the effect of leachate content in fluid mixture becomes negligible. Therefore, the effect of changing p_l is more significant at lower values of *w*.

Figures 8a–8e compares the resistivity values measured by gradually increasing the amount of Leachates #1, #2 and #3 in the pore fluid. Figure 8a gives the results obtained by using a fluid content *w* of 4%. Figures 8b–8e give similar results for *w* of 8%, 12%, 16% and 20%.

It is noted that although the compositions of the three leachates are quite different (Table 3); Leachates #1 and #2 have similar effects. It is also observed that the resistivity values are higher for Leachate #3 in comparison to the other two leachates. Furthermore, it is interesting to note that the pH of the Leachates #1 and #2 is the same, i.e. 7.90, while the pH of Leachate #3 is much higher, i.e. 10.24 (Table 3). Hence, it might be possible that the pH values of the leachates could account for the observations for resistivity, as soil resistivity is largely influenced by the properties of its pore fluids (Yoon and Park 2001).

For fluid contents greater than 12%, it is observed from the figures that the disparity between the resistivity values of Leachate #1, #2 and #3 is considerably reduced. Additionally, with increasing leachate content, this disparity was found to

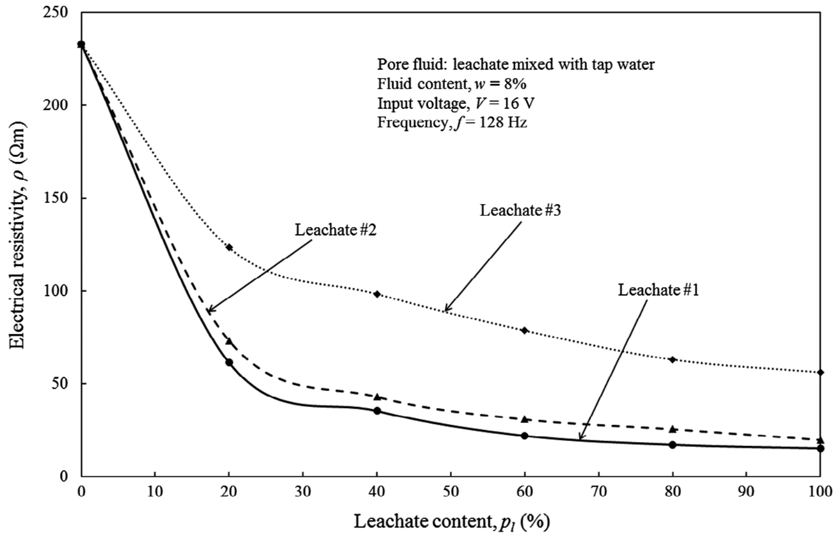

Figure 8b. Comparison of Leachate #1, Leachate #2 and Leachate #3 at fluid content of 8%.

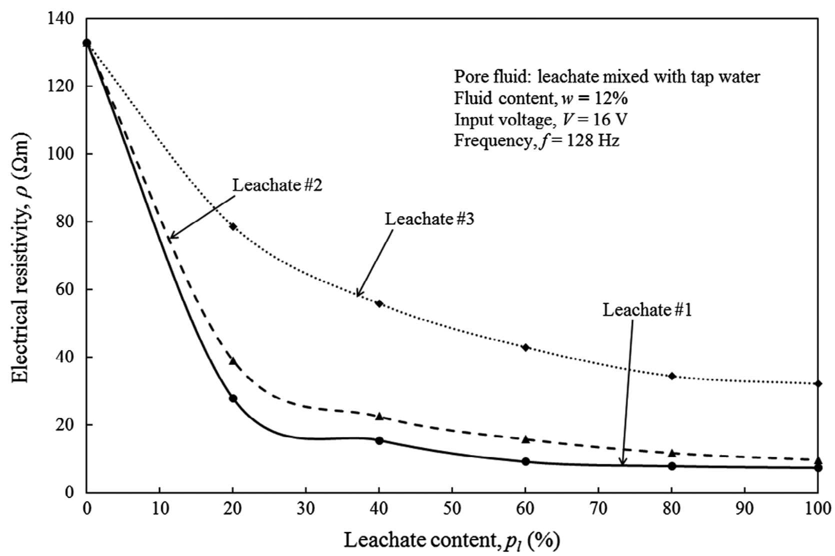

Figure 8c. Comparison of Leachate #1, Leachate #2 and Leachate #3 at fluid content of 12%.

decrease. However, the reduction in resistivity following on from increases in w is more pronounced than the reduction observed due to increases in p_l. Hence, it is inferred that the effect of the fluid content is more significant than the effect of either the content or the type of leachate.

From Figures 6a–6c, it is observed that the resistivity $\rho(\Omega\text{m})$ is inversely proportional to the fluid content w (%). Their relationship follows the trend given by the following:

$$\rho \propto \frac{1}{w} \tag{5}$$

Similar observations have been recorded by previous researchers (Archie 1942; McCarter 1984; Mccarter and Desmazes 1997). Pandey, Shukla and Habibi (2015) developed the correlation of resistivity ρ with the relative density D_r (%) and fluid content w (%) for Perth sandy soil. In this study, tap water and distilled water were used as pore fluids. The correlation is as follows:

$$\rho = a_1\left(a_2 - \frac{D_r}{100}\right)(w)^{-a_3} \tag{6}$$

where a_1 (Ωm), a_2(dimensionless) and a_3(dimensionless) are specific constants corresponding to a specific soil type and pore fluid.

Using a regression analysis for the results obtained in this study, and also using the correlations developed by Pandey, Shukla, and Habibi (2015); the correlation of resistivity ρ with the relative density D_r(%), leachate content (p_l) and fluid content w(%) for the sandy soil can be given by:

$$\rho = c_1 C_o\left(c_2 - \frac{D_r}{100}\right)\left[(w)^{-\left(\frac{100c_3C_o}{p_l}\right)}\right] \tag{7}$$

where c_1(Ωm), c_2(dimensionless), and c_3(dimensionless) are specific constants corresponding to a particular soil type and

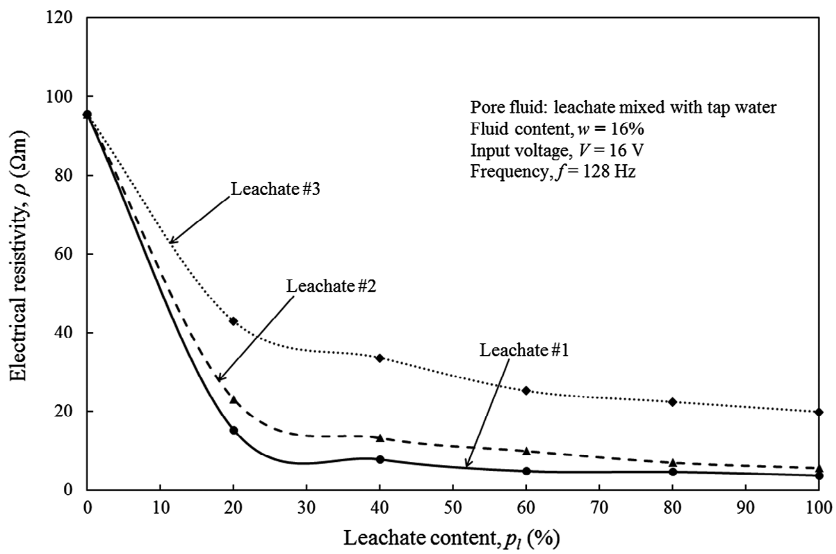

Figure 8d. Comparison of Leachate #1, Leachate #2 and Leachate #3 at fluid content of 16%.

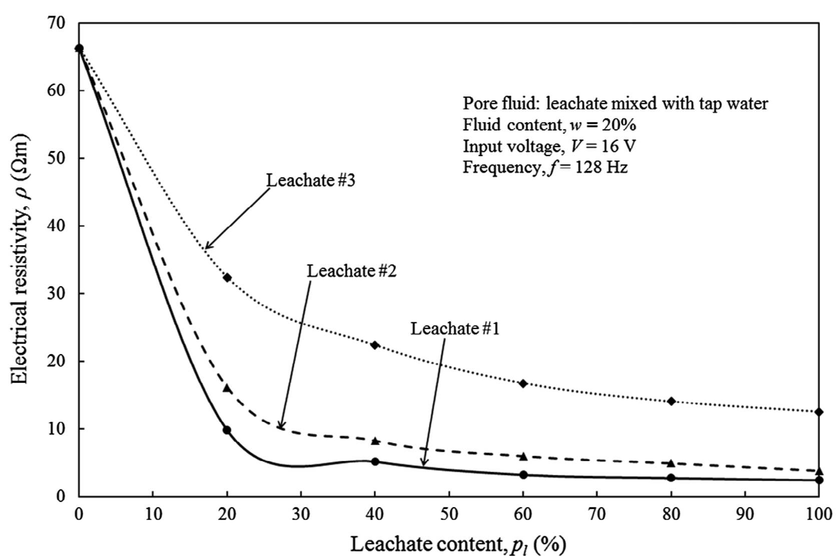

Figure 8e. Comparison of Leachate #1, Leachate #2 and Leachate #3 at fluid content of 20%.

pore fluid, and C_0(dimensionless) is a variable dependent on the composition of the pore fluid. Here, C_0 is found to increase along with increase in the leachate content.

Conclusions

This study presents the results of an investigation into the effect of contamination of Perth landfill base soil, with leachates, on its electrical resistivity. Based on the results and discussion presented earlier, the following general conclusions can be drawn:

(1) The addition of even a small amount of leachate to the pore fluid mixture results in a marked decrease in the electrical resistivity of the landfill base soil. Hence, the use of the electrical resistivity method can be an extremely viable option for contamination detection.
(2) The resistivity exhibits a rapid decrease with increasing fluid content. However, the rate of decrease is significantly reduced for fluid contents over 9%, irrespective of the leachate type and content.
(3) For the three leachates used in this study, increasing the amount of leachate content of the fluid mixture results in a decrease in the resistivity. The rate of decrease is more significant for leachate content less than 20%, irrespective of the leachate used.
(4) The effect on the electrical resistivity of the soil mixture, from changing the fluid content is more significant than the effect produced by varying the type or the content of leachate.
(5) New correlations were developed from this study which can be used by land filling authorities to predict the electrical resistivity of sandy base soil infiltrated by leachates.
(6) The results of this study may be useful for waste storage and handling operators in monitoring and subsequent

treatment of base soil contamination. Furthermore, the study can also be useful for the development of sensors for early leakage detection to effectively manage the generation, prevention and mitigation of environmental pollution.

Notation

a_1	constant (Ωm)
a_2 and a_3	constants corresponding to a particular soil type and pore fluid (dimensionless)
c_1	constant (Ωm)
c_2 and c_3	constants corresponding to a particular soil type and pore fluid (dimensionless)
C_c	coefficient of curvature (dimensionless)
C_o	variable dependent on the composition of the pore fluid (dimensionless)
C_u	coefficient of uniformity (dimensionless)
D_{10}	effective size of the soil particles (mm)
D_r	relative density (dimensionless)
f	input frequency (Hz)
G_s	specific gravity of soil solids (dimensionless)
p_l	leachate content of the water-leachate mixture (dimensionless)
R	electrical resistance (ohm, Ω)
V	potential difference across the outer conductors/input voltage (V)
V_f	total fluid volume (m^3)
V_l	leachate volume (m^3)
w	fluid content (dimensionless)
W_f	weight of fluid (g)
W_s	weight of sand (g)
γ	total unit weight of soil (kN/m^3)
γ_d	dry unit weight of soil (kN/m^3)
γ_{dmax}	maximum dry unit weight of soil (kN/m^3)
γ_{dmin}	minimum dry unit weight of soil (kN/m^3)
ρ	electrical resistivity of the soil (Ωm)

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Disclosure statement

No potential conflict of interest was reported by the authors.

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