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Influencing factors on electrical conductivity of compacted kaolin clay

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Abstract. The electrical conductivity of a soil-water system is related to its engineering properties. By measuring the soil electrical conductivity, one may obtain quantitative, semi-quantitative, or qualitative information to estimate the in-situ soil behavior for site characterization. This paper presents the results of electrical conductivity measured on compacted kaolin clay samples using a circular two-electrode cell in conjunction with a specially designed compaction apparatus, which has the advantage of reducing errors due to sample handling and increasing measurement accuracy. The experimental results are analyzed to observe the effects of various parameters on soil electrical conductivity, i.e. porosity, unit weight, water content and pore water salinity. The performance of existing analytical models for predicting the electrical conductivity of saturated and unsaturated soils is evaluated by calculating empirical constants in these models. It is found that the Rhoades model gives the best fit for the kaolin clay investigated. Two general relationships between the formation factor and soil porosity are established based on the experimental data reported in the literature and measured from this study for saturated soils, which may provide insight for understanding electrical conduction characteristics of soils over a wide range of porosity.

Keywords: compaction; electrical conductivity; formation factor; kaolin clay; salinity.

1. Introduction

The interaction between an external electric field and a soil-water system can be characterized in terms of the electrical conductivity, which represents the mobility of electrical charges through soil mass. The electrical conductivity of any earth material reflects its physical, chemical and geological properties. It is noteworthy that the electrical resistivity is also used in engineering practice, which is the reciprocal of the electrical conductivity.

The study on electrical response of soil-water systems is an emerging field with applications in areas including agriculture, soil science, geotechnical and environmental engineering. Reliable measurement of soil electrical conductivity is essential for broad engineering applications, such as the assessment of soil salinity and water content (Kalinski and Kelly 1993, Hamed *et al.* 2003), monitoring solute transport through soils (Kachanoski *et al.* 1992, Vanclooster *et al.* 1995), exploration of oil and hydrocarbon in brine-bearing reservoirs (Kim and Manghnani 1992, Wheatcroft

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2002), estimation of hydraulic properties of soils (Lovell 1985, Gorman and Kelly 1990), performance evaluation of compacted-soil liners (Kalinski and Kelly 1994, Abu-Hassanein *et al.* 1996), characterization of liquefaction potential of soils (Erchul and Gluarte 1982, Arulanandan and Muraleetharan 1988), and engineering applications of electrokinetics (Mohamedelhassan and Shang 2003, Rittirong *et al.* 2008, Shang *et al*. 2009).

Electrical conductivity of soils can be measured in the laboratory, generally by using either time domain reflectometry (TDR) or soil resistivity boxes. However, TDR technique is expensive, and overestimates the electrical conductivity of highly saline soils (e.g. higher than 0.05 S/m, Nichol *et al.* 2002) that leads to inaccurate estimate of water content (Hamed *et al.* 2003). On the other hand, soil resistivity boxes are relatively cost effective and simple to conduct. The standard method for electrical conductivity tests of soils is specified in ASTM G 57 (ASTM 2006). For laboratory experimentation, soil is filled in a rectangular soil box. Four electrodes, i.e. a pair of outer electrodes as the current electrodes and a pair of inner pin-shaped electrodes as the potential electrodes, are employed.

As an alternative to use a standard soil box, some measurement systems have been reported in the literature. A cylinder with two electrodes arranged horizontally or vertically was designed by McCarter (1984) and Rinaldi and Cuestas (2002). In this device, a pair of end plate electrodes was used as both the current and potential electrodes. Another measurement device given in the literature consisted of a circular cell that incorporates eight holes at 45° intervals for the insertion of electrodes (Rhoades *et al.* 1976, Kalinski and Kelly 1993, Auerswald *et al.* 2001). Measurements were obtained eight times around the circular cell, moving each set of four adjacent electrodes, known as a Wenner array, and the average of the resistances was taken. Abu-Hassanein *et al.* (1996) developed a four-electrode cell with dimensions of the compaction mold described in ASTM D 698 (ASTM 2007). More recently, multi-electrode cells with several circumferential electrodes were fabricated to investigate the electrical anisotropy of soils (McCarter and Desmazes 1997, Bryson and Bathe 2009). The aforementioned measurement systems, however, have some limitations: 1) it is difficult to achieve uniform compaction of soil, followed by the variation of soil density in the box, and 2) it may result in poor contacts at the soil-electrode interface from insertion of electrodes. To compensate for these uncertainties in measurement, a circular two-electrode cell in conjunction with a specially designed compaction apparatus was developed in Scholte *et al.* (2002), which was adopted in this study.

The objective of this study is to present the results of the electrical conductivity measurement on compacted kaolin clay at different porosities, unit weights, water contents and pore water salinities, and to demonstrate the characteristic electrical responses with respect to these parameters. The experimental results are also analyzed to compare the existing prediction models of electrical conductivity of saturated and unsaturated soils, together with computing the empirical constants in these models.

2. Background

2.1 Influencing factors on soil electrical conductivity

Several researchers (Jackson *et al.* 1978, Abu-Hassanein *et al.* 1996, Rinaldi and Cuestas 2002) have shown that the electrical conductivity of a soil-water system is related to inherent factors such as the particle size, shape, gradation, orientation and mineralogical composition, and to more variable factors including the porosity, degree of saturation, water content, temperature, concentration and type of electrolytes, and frequency of the electrical field for the measurement.

Three parameters used to define the amount of water in bulk soil are: the gravimetric water content w (the weight ratio of water to solid), the degree of saturation S (the volumetric ratio of water to void) and the volumetric water content θ (the volumetric ratio of water to bulk soil). The parameters are correlated in soil phase relations

$$\theta = w\frac{\gamma_d}{\gamma_w} = Sn \tag{1}$$

where γ_w is the unit weight of water, γ_d is the dry unit weight of soil, and n is the soil porosity given as

$$n = 1 - \frac{\gamma_d}{G_s \gamma_w} \tag{2}$$

where G_s is the specific gravity of soil solid. Note that the volumetric water content is equal to soil porosity when the soil is fully saturated.

The electrical conductivity of soils is comprised of three components, i.e. the pore water electrical conductivity, surface electrical conductivity and solid electrical conductivity. The pore water contributes to the electrical conductivity through electromigration of dissolved ions, which is dependent upon the salinity (ionic strength), temperature and the frequency imposed to ions. It is noteworthy that the term salinity represents the overall effect of dissolved ionic species such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, CO_3^-, HCO_3^-, SO_4^-, etc in an aqueous solution (Hamed *et al.* 2003). The pore water electrical conductivity, therefore, is a reliable indicator to assess the concentration of soluble salts in soils (U.S. Salinity Laboratory Staff 1954). The second component of soil electrical conductivity, i.e. the surface electrical conductivity, is attributed to migration of absorbed counterions on the surface of soil solids. The surface electrical conductivity dominates over the electrical conductivity of solids in soils with low salinities, and is influenced by the soil fabric (which refers to the arrangement of grains of all size ranges, shapes and associated pores) as well as by organic matters (Auerswald *et al.* 2001). The third component of soil electrical conductivity, i.e. the solid electrical conductivity, is typically much lower than the surface electrical conductivity and hence can be neglected.

2.2 Electrical conductivity models for soil

Archie (1942) established a simple one-conductance model accounting only for the contribution of water phase in completely saturated soils. The bulk soil electrical conductivity of a fully water-saturated soil κ_0 is related to the pore water electrical conductivity κ_w as a function of soil porosity n, according to

$$\kappa_0 = n^m \kappa_w \tag{3}$$

where m is the constant termed the cementation exponent, which increases with increasing the soil cementation. According to Abu-Hassanein *et al.* (2001), the cementation exponent is affected by compaction and anisotropy, as well as fabric.

Winsauer *et al.* (1952) modified Archie model by introducing a tortuosity factor c, yielding

$$\kappa_0 = cn^m \kappa_w \tag{4}$$

The c and m may be considered to be covariant because both are not independent parameters. It is commonly accepted that the increase in soil density by compaction leads to increasing the tortuosity factor (Salem 2001).

Since soil pore water flows through similar paths as the electric current, both the hydraulic and electrical conductivities of soils may be thought to be linked by a single parameter, the tortuosity τ which is defined as the ratio of the effective length of a flow path to the straight length of a porous media. Based on this concept, the theoretical relationship between the tortuosity and normalized electrical conductivity κ_w/κ_0 (known as the formation factor F) was derived by Walsh and Brace (1984)

$$\tau = \sqrt{n\frac{\kappa_w}{\kappa_0}} \tag{5}$$

As the degree of saturation S decreases, the bulk soil electrical conductivity will decrease, because some of the pore space formerly occupied by water is replaced by air of low electrical conductivity. The electrical conductivity of unsaturated soil κ_b is related to that of fully saturated soil κ_0 (Keller and Frischknecht 1966) by

$$\kappa_b = \kappa_0 S^p \tag{6}$$

where p is the saturation exponent. It should be noted that Eq. (6) was developed for porous media having fixed pore structure that has no blockage to continuous flow.

On the other hand, the electrical conductivity of unsaturated soils can be characterized in terms of the volumetric water content θ. Rhoades *et al.* (1976) proposed a two-conductance model which is most widely used in soil science. The predominant conductance is through the pore water, and the contribution of soil solids takes place along the continuous films of exchangeable cations that reside on the surface of charged solid particles. Accordingly, the soil electrical conductivity can be regarded as being analogous to two electric conductors in parallel, expressed by

$$\kappa_b = (a\theta^2 + b\theta)\kappa_w + \kappa_s \tag{7}$$

where κ_s is the surface electrical conductivity, a and b are empirical constants, and other parameters have been defined before. Hamed *et al.* (2003) reported that values of a and b lie in the range of −14.0 to 9.7 and −6 to 14.2, respectively.

Shah and Singh (2005) suggested a generalized form of Archie model for unsaturated soils, in which surface conductance effect was neglected, as a function of the volumetric water content θ with two constants α and β

$$\kappa_b = \alpha\kappa_w\theta^\beta \tag{8}$$

They believed that the empirical constants determined by the measured electrical conductivity will implicitly reflect the influence of the soil solid conductance. The values of α and β are in the range of 0.33 to 15.85 and 0.74 to 3.92, respectively.

3. Experimental investigation

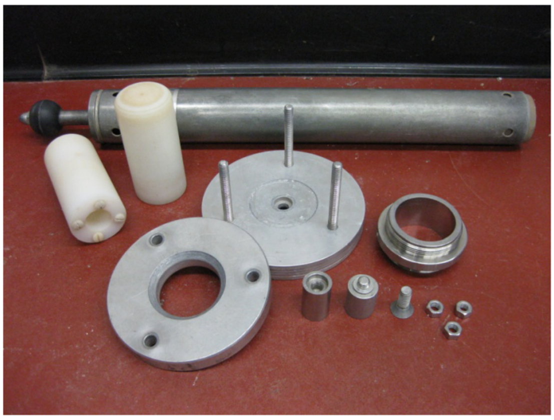
3.1 Materials and equipments

A commercially processed kaolin clay was used in this study. The index properties of the kaolin clay are summarized in Table 1. The soil was oven dried at 105°C because no water may be initially present before mixing with electrolytes. Three types of electrolyte solutions were employed to create pore water with different electrical conductivities: solutions of sodium chloride (NaCl) at molar concentrations of 0.03, 0.1 and 0.2 mol/L. The NaCl solutions were made by dissolving NaCl in deionized water (electrical conductivity of < 1 μS/m). A predetermined weight of the dried clay was mixed with a NaCl solution of known weight to obtain the desired gravimetric water content, and then stored in sealed containers for over 24 hrs.

A circular two-electrode cell in conjunction with a compaction apparatus is shown in Fig. 1. The

Table 1 Index properties of kaolin clay tested

Parameters	Kaolin clay
Soil classification (USCS)	CH
Specific gravity (–)	2.61
Liquid limit (%)	73
Plastic limit (%)	39
Plasticity index (%)	34
% Finer sieve # 200	97.6
Clay (< 0.002 mm) (%)	15.9
Maximum dry unit weight (kN/m^3)	14.1
Optimum gravimetric water content (%)	28.7
Void ratio at optimum gravimetric water content (–)	0.80
Cation exchange capacity (CEC) (meq/100 g)	5.82



(a) Dissembled compaction cell and standard Proctor hammer

(b) Assembled compaction cell

Fig. 1 Circular two-electrode cell and compaction apparatus

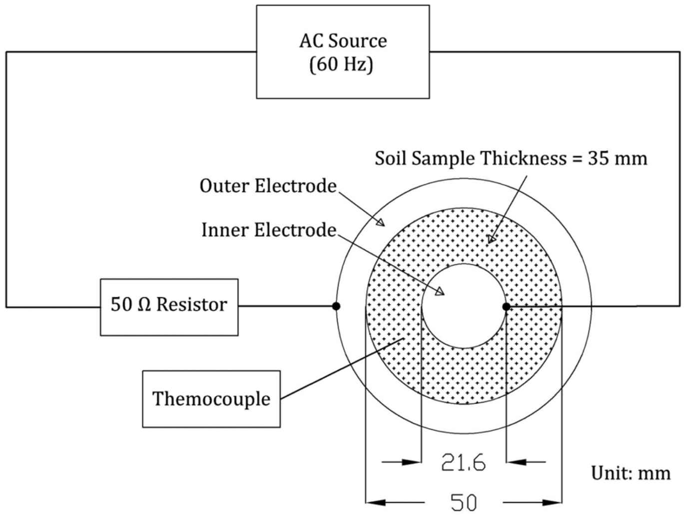


Fig. 2 Schematic of the electrical conductivity measurement system

circular two-electrode cell consists of an outer electrode and an inner electrode, made of stainless steel. The cell houses an annular soil sample with 50 mm outer diameter, 21.6 mm inner diameter and 35 mm thickness. The compaction apparatus was designed to achieve uniform compaction and to eliminate gaps between the soil sample and cell. The apparatus comprises top and bottom plates held together by connecting bolts. The bottom plate has an inset ring on which the base of the outside electrode is located. The inside electrode placed on the bottom plate is secured on a threaded rod to ensure its location on the center of the outside electrode during compaction. The top plate has a circular opening and an inset ring of the same size as the inside diameter of the outer electrode. The plate is used to hold the outside electrode in place during compaction. The compaction is carried out through a standard Proctor hammer through an annular ram that has slightly smaller diameter than the cell. An extension sleeve is added to the center electrode as a guide for the ram. The soil sample is compacted in two layers. For better continuity at the interface between the compacted two layers, the base of ram is fitted with small prominent points that provide additional kneading action when the soil sample is compacted. After compaction, the excess soil is trimmed off using the top edge of the outer electrode as a guide.

An AC source is connected in series to a test specimen and a 50 Ω resistor, generating a radial electrical field through the soil sample compacted in the annular space of the cell, as illustrated in Fig. 2. The voltage across the soil sample between the inner and outer electrodes is measured using a digital multimeter, and then the current is calculated indirectly by measuring the voltage across the 50 Ω resistor. The electrical conductivity of the soil compacted in the cell can be determined by knowing the dimensions of the cell, applied voltage V and current I (Scholte *et al.* 2002)

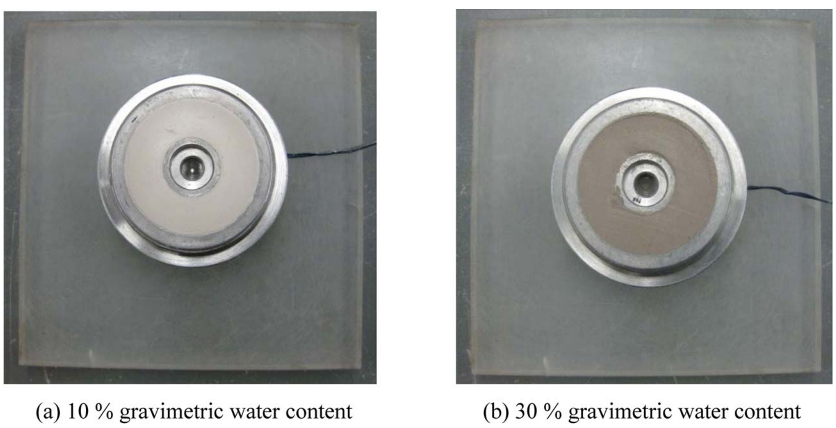
$$\kappa_b = \frac{\left(\ln\frac{r_i}{r_o}\right) I}{2\pi t V} \tag{9}$$

where r_o and r_i are radii of outer and inner electrode, t is the soil sample thickness. In this study, the electrical conductivity measurement on the soil sample was made under the frequency of 60 Hz. It is based on the experimental evidence discussed in Abu-Hassanein *et al.* (1996), indicating that this frequency is high enough to have negligible effects of electrode polarization.

3.2 Experimental methods

The soil cured was compacted directly into the circular two-electrode cell, according to the equipment setup described above. The density of the soil sample was controlled by blow counts of the hammer (i.e. compaction energy). Fig. 3 displays the uniformly compacted soil samples with gravimetric water contents of 10% and 30%, showing that good contacts were attained between soil and electrodes. Following compaction, the electrical conductivity of the soil sample was measured. The electrical measurement on all samples was performed at the temperature of $19 \pm 1°C$. Within this range, the temperature dependency of electrical conductivity is quite small and negligible. After measurement, the weight of soil sample was precisely measured for calculation of the bulk unit weight, and afterwards a small portion of soil was taken from the top and bottom of the cell to confirm the corresponding desired gravimetric water content of the sample. The porosity, degree of saturation and volumetric water content of the soil samples were calculated by using Eqs. (1) and (2).

The pore water electrical conductivity of the kaolin clays mixed with three NaCl solutions was determined following the standard method described in U.S. Salinity Laboratory Staff (1954). At each NaCl concentration, seven saturated pastes, mixed with clay-to-solution weight ratios of 0.1 to 1.5, were prepared. The pastes were mechanically agitated for one hour and then centrifuged at 5000 rpm for 15 min. Lastly, the electrical conductivities of decanted solutions were measured using a hand-held electrical conductivity probe. The results of electrical conductivity measurement on a total of 24 solutions tested including pure NaCl solutions are depicted in Fig. 4. The electrical conductivity of decanted solution increases slightly as the clay-to-solution weight ratio increases. It is attributed to dissolving some of free and absorbed ions in kaolin clay into the solution. The electrical conductivities of the decanted solutions obtained from pastes with the clay-to-solution weight ratio of 1.5 were considered to be the pore water electrical conductivities of three saline kaolin clays: 0.289, 1.084, and 2.050 S/m (see Table 2). These values are within the possible salinity range of in-situ soils (Rhoades *et al.* 1976, Shah and Singh 2005).



(a) 10 % gravimetric water content (b) 30 % gravimetric water content

Fig. 3 Compacted annular soil samples in the cell

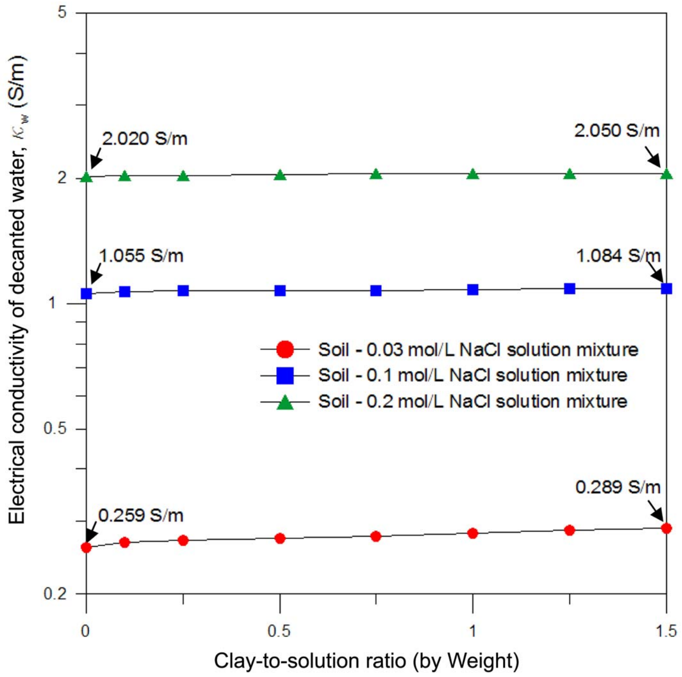


Fig. 4 Variation of electrical conductivity against clay-to-solution ratio for decanted solutions

4. Results and discussion

A summary of experimental results for all soil samples tested is presented in Table 2. The data interpretation was focused on the relationships of the bulk soil electrical conductivity with the soil porosity, dry unit weight, pore water salinity, and water contents (gravimetric water content, degree of saturation and volumetric water content). The relations are of fundamental importance to site characterization and other engineering applications (Arulanandan and Muraleetharan 1988, Kaya and Fang 1997).

4.1 Effect of soil porosity: saturated samples

The relationship between the soil porosity and formation factor for saturated soil samples (Nos. 13-15, 28-31, 45-47, see Table 2) is shown in Fig. 5. It should be noted that soil samples with the degree of saturation above 0.99 are considered to be fully saturated owing to the limitation of the test methodology used. The soil porosity lies within the range of about 0.53 to 0.60, which is consistent with results reported by Kezdi (1974), i.e. soil porosity typically varies from 0.45 to 0.70 for silty clays. The formation factor decreases as the soil porosity increases, indicating that at a given pore water salinity, the bulk soil electrical conductivity of saturated kaolin clay increases with increasing the porosity. This is due to the fact that conduction in saturated soil is dominated by pore water content. On the other hand, Fig. 5 shows the somewhat scatter of experimental data about a best fit curve but which is systematic. It may be attributed that the effect of surface conductance depending on soil salinity that contributes to difference in the formation factor. According to Archie

Table 2 Summary of soil sample properties

Sample	w (%)	γ_d (kN/m^3)	n (−)	S (%)	θ (−)	κ_w (S/m)	κ_b (mS/m)
1	9.2	10.3	0.597	16.2	0.097	0.289	5.1
2	9.4	11.3	0.557	19.5	0.109	0.289	7.0
3	9.3	12.9	0.496	24.7	0.122	0.289	8.2
4	20.2	10.3	0.598	35.4	0.212	0.289	13.9
5	20.1	11.1	0.567	40.1	0.227	0.289	15.0
6	20.4	11.9	0.536	46.1	0.247	0.289	18.6
7	30.3	9.9	0.612	50.1	0.307	0.289	23.9
8	30.3	10.7	0.581	57.1	0.332	0.289	30.1
9	30.4	11.6	0.549	65.3	0.358	0.289	36.4
10	37.6	12.5	0.513	93.1	0.478	0.289	66.9
11	37.7	12.7	0.504	97.0	0.488	0.289	70.3
12	37.8	12.8	0.501	98.2	0.492	0.289	72.4
13	45.9	11.6	0.547	99.2	0.543	0.289	84.2
14	50.8	11.0	0.571	99.7	0.569	0.289	92.5
15	55.9	10.4	0.594	99.7	0.593	0.289	101.6
16	7.6	11.0	0.570	15.0	0.085	1.084	7.2
17	7.8	11.5	0.550	16.7	0.092	1.084	11.0
18	7.6	12.8	0.499	19.9	0.099	1.084	13.8
19	18.8	10.4	0.596	33.3	0.198	1.084	27.0
20	18.9	11.3	0.558	39.0	0.218	1.084	37.4
21	18.7	12.7	0.504	48.0	0.242	1.084	47.2
22	27.2	10.6	0.585	50.4	0.295	1.084	61.5
23	27.2	11.6	0.547	58.7	0.321	1.084	79.9
24	27.4	12.2	0.523	65.2	0.341	1.084	97.8
25	39.8	12.3	0.520	95.8	0.498	1.084	239.8
26	39.7	12.4	0.516	97.3	0.502	1.084	249.7
27	39.9	12.4	0.515	98.3	0.506	1.084	260.5
28	42.9	12.1	0.528	100.1	0.529	1.084	283.4
29	44.7	11.8	0.541	99.2	0.537	1.084	288.2
30	48.0	11.4	0.556	99.9	0.556	1.084	313.3
31	49.9	11.1	0.568	99.2	0.563	1.084	336.4
32	9.4	10.1	0.606	15.9	0.097	2.050	11.0
33	9.4	10.8	0.577	18.0	0.104	2.050	15.6
34	9.3	12.8	0.502	24.1	0.121	2.050	23.5
35	18.7	11.0	0.569	36.9	0.210	2.050	50.0
36	18.5	11.8	0.540	41.1	0.222	2.050	62.1
37	18.6	12.1	0.526	43.8	0.230	2.050	68.4
38	18.5	12.9	0.496	49.1	0.243	2.050	82.9
39	30.3	11.5	0.552	64.2	0.354	2.050	167.7
40	30.2	12.3	0.520	72.7	0.378	2.050	201.5
41	30.4	12.7	0.502	78.6	0.395	2.050	236.2
42	39.6	12.1	0.527	92.7	0.489	2.050	366.1
43	39.5	12.3	0.518	95.7	0.496	2.050	383.8
44	39.5	12.5	0.513	97.9	0.502	2.050	400.5
45	45.4	11.7	0.544	99.4	0.541	2.050	511.5
46	49.0	11.2	0.563	99.2	0.559	2.050	561.8
47	57.2	10.2	0.600	99.6	0.598	2.050	596.9

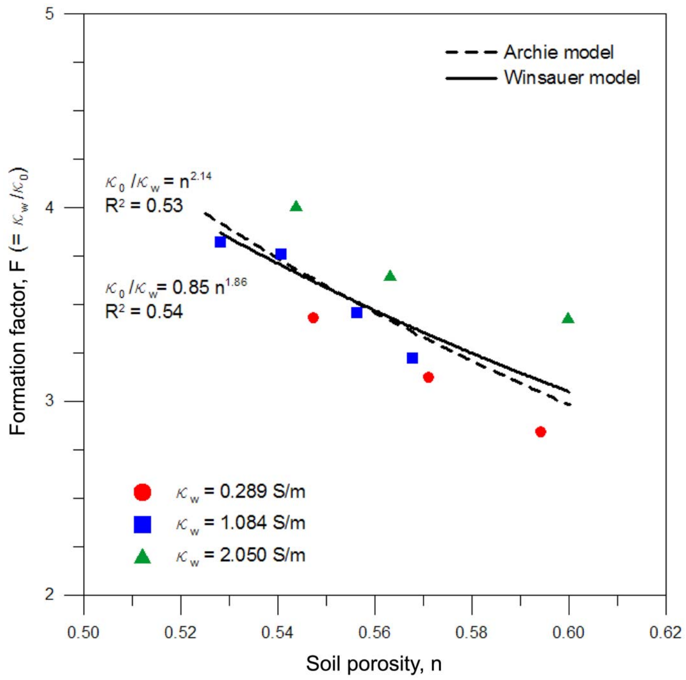


Fig. 5 Formation factor of saturated samples with different salinities against soil porosity

model, i.e. Eq. (3), the cementation exponent calculated from the regression analysis is determined to be 2.14 with $R^2 = 0.53$. Based on Winsauer model, i.e. Eq. (4), the cementation exponent and tortuosity factor are analyzed to be 1.86 and 0.85 with $R^2 = 0.54$. These values are comparable to those reported in literature (see Table 3).

For more than 60 years, the relation between the formation factor and soil porosity has been extensively studied for natural geo-materials (i.e. soils and rocks) obtained from offshore and onshore areas as well as artificial materials such as ploydisperse glass spheres and fused glass beads. Of these materials, the electrical responses of soils were reviewed, and the summary of the empirical constants in Eqs. (3) and (4) for various soils is given in Table 3, together with the number of data available for each of them. The values of the constants were obtained directly from the literature or calculated from the reported data of formation factor as a function of soil porosity. It is revealed that practically the cementation exponent in Archie model falls within the limits of 1.27 and 2.29 for soils, although Wyllie and Gregory (1953) pointed out that it can theoretically range from one to infinity. For Winsauer model, the cementation exponent and tortuosity factor are in the ranges of 0.45 to 1.52 and 0.86 to 2.49, respectively.

This study includes the quantification of the empirical constants in both Archie and Winsauer models based on a number of measurements on the formation factor with respect to soil porosity. Fig. 6 illustrates the general relationships between the formation factor and soil porosity for reported data considered in Table 3. Over a wide range of soil porosities (0.2-0.9), the formation factor decreases from 16.0 to 1.5 with increasing the porosity. The experimental data of this study are comparatively in good agreement with reported data. In Fig. 6, the dotted line represents Archie model ($m = 1.65$ with $R^2 = 0.65$), and the solid line corresponds to Winsauer model ($c = 0.71$ and $m = 1.27$ with $R^2 = 0.73$). The two general relations can enhance the understanding of electrical

Table 3 Cementation exponent (m) and tortuosity factor (c) for various soils

Site	Medium	No. of Samples	Porosity n	Archie model	Winsauer model		References
				m	m	c	
Onshore	Aquifer sands	62	0.25-0.50	1.48	0.78	1.24	Jones and Buford (1951)
Offshore	Sandy soils	42	0.58-0.87	2.29	0.77	1.45	Boyce (1968)
Offshore	Marine sands	42	0.38-0.48	1.54	0.82	1.31	Jackson (1975)
Offshore	Marine sands	35	0.33-0.50	1.45	0.61	0.91	Jackson *et al.* (1978)
Offshore	Sandy soils	19	0.49-0.72	1.98	0.94	1.86	Hulbert *et al.* (1982)
Onshore	Sands	44	0.23-0.45	1.54	0.87	1.42	Biella *et al.* (1983)
Offshore	Marine clays	26	0.52-0.71	1.94	0.78	1.42	Lovell (1985)
Offshore	Marine sediment	13	0.27-0.77	1.76	0.77	1.45	Lavoie *et al.* (1988)
Onshore	Ottawa sands	8	0.36-0.42	1.63	0.52	0.91	Gorman and Kelly (1990)
Offshore	Carbonated sands	29	0.30-0.61	1.47	0.62	0.86	Bennett *et al.* (1990)
Offshore	Weathered chalk	41	0.26-0.55	2.00	0.45	1.07	Kim and Manghnani (1992)
Offshore	Calcareous ooze	35	0.52-0.72	2.14	0.96	2.07	Kim and Manghnani (1992)
Onshore	Glacial aquifer	19	0.25-0.51	2.07	0.80	1.87	Salem (2001)
Offshore	Carbonate sands	6	0.37-0.50	1.27	0.71	0.88	Wheatcroft (2002)
Onshore	Loess	8	0.33-0.49	2.04	1.52	2.49	Rinaldi and Cuestas (2002)
Onshore	Tuff grains	4	0.60-0.64	1.66	0.82	1.23	Friedman and Robinson (2002)
Onshore	Quartz sands	7	0.40-0.44	1.45	0.74	1.11	Friedman and Robinson (2002)
Onshore	Kaolin clay	7	0.53-0.60	2.14	0.85	1.86	This study

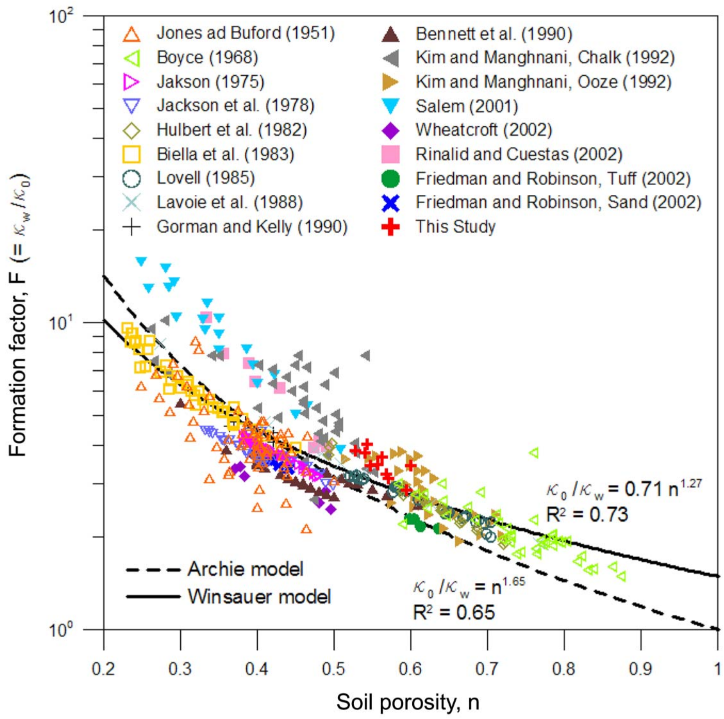


Fig. 6 General relationships between formation factor and soil porosity for measured and reported data

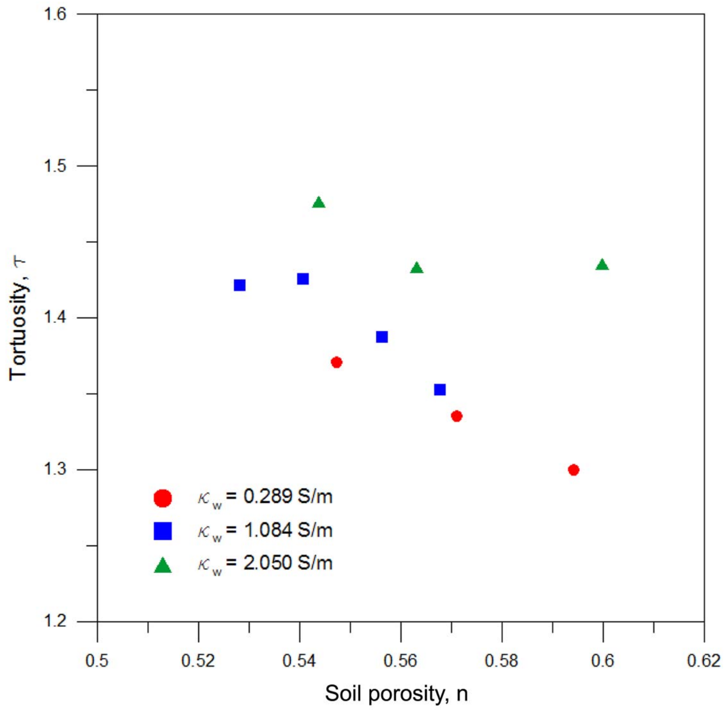


Fig. 7 Tortuosity of saturated samples with different salinities against soil porosity

conduction characteristics of soils over a wide porosity range as well as predicting the soil porosity with known formation factor.

From the experimental results of kaolin clay, the tortuosity is determined according to Eq. (5). Fig. 7 shows that the tortuosity decreases with increasing soil porosity at a given soil salinity. Similar observation is investigated in the literature (Salem and Chilingarian 2000). The result provides evidence to support the hypothesis that in case of lower porosity, both the hydraulic flow and electric current can be forced to take a longer and more tortuous path that leads to increasing resistance and higher tortuosity.

4.2 Effect of gravimetric water content

The relationships between the bulk soil electrical conductivity, dry unit weight and gravimetric water content at three soil pore water salinities are depicted in Fig. 8. In each case, a distinct relation between the bulk soil electrical conductivity and dry unit weight of soil is noted. The figure indicates that the bulk soil electrical conductivity is sensitive to the gravimetric water content and dry unit weight. The bulk soil electrical conductivity increases as the gravimetric water content increases, as would be expected. Moreover, increasing the gravimetric water content causes the steeper slope of the bulk soil electrical conductivity versus dry unit weight curve, associated with that particular gravimetric water content. This means that the effect of soil unit weight on the bulk soil electrical conductivity becomes more important at the higher gravimetric water content. On the other hand, it is observed under the same gravimetric water content that the bulk soil electrical conductivity increases with increasing the dry unit weight. This is attributed to the fact that, with

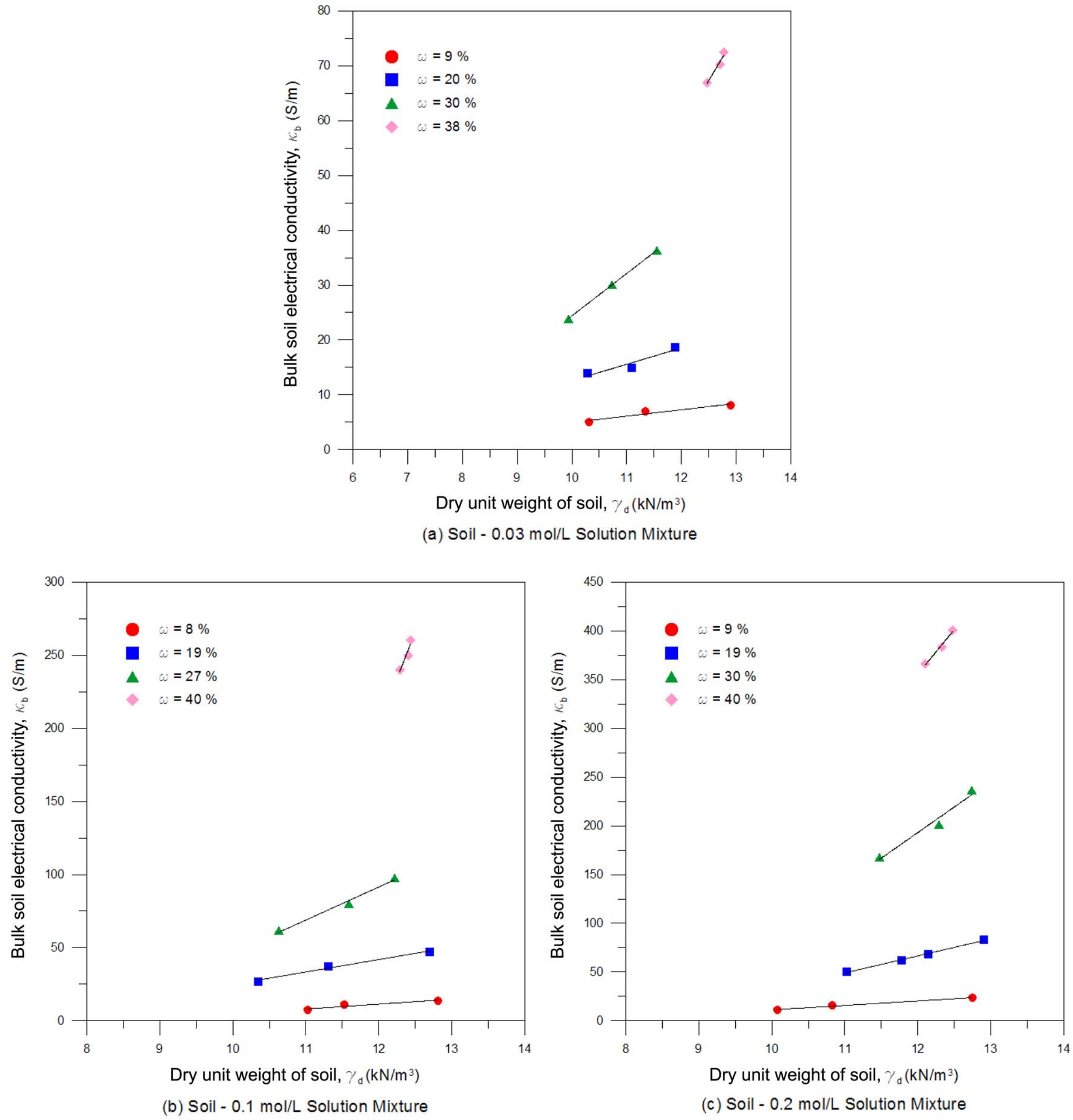


Fig. 8 Influence of gravimetric water content and dry unit weight on bulk soil electrical conductivity

the increase in the dry unit weight, the volumetric water content increases as well, which results in a higher bulk soil electrical conductivity. From these results, it can be inferred that the soil gravimetric water content is not the sole influencing factor to the bulk soil electrical conductivity even if the pore water salinity is kept constant. This is parallel to the fact that conduction of current in soil is controlled by the volumetric fraction of constituents (especially, the volumetric water content) in a soil. However, the observation on soil electrical behavior with respect to the dry unit weight of soil at constant gravimetric water content is still significant because this is the case for a compacted earth fill where water is uniformly distributed in the soil but not compaction energy.

4.3 Effect of degree of saturation

The variation of the bulk soil electrical conductivity against the degree of saturation under various pore water salinities is presented in Fig. 9. It is seen that as the degree of saturation decreases, the bulk soil electrical conductivity decreases. This is due to the fact that the continuous film of soil pore water over soil solid surfaces becomes thinner and the conducting channels become considerably tortuous. On the other hand, the bulk soil electrical conductivity increases when the pore water salinity increases. This behavior is generally observed in particulate-type materials in which water (for instance) phase is distributed within a matrix (Rinaldi and Cuestas 2002). Fig. 9 displays that for a given soil salinity, a unique relationship between the bulk soil electrical conductivity and degree of saturation exists, which is independent of the soil unit weight. However, at 100% saturation, considerable scattering of data is observed, especially at higher pore water salinity. It is attributed that the volumetric water content at 100% saturated soil can be varied with different porosities (see Eq. (1)) that produces different bulk soil electrical conductivities. Furthermore, the surface conductance that depends on soil salinity and water content may affect the bulk soil electrical conductivity.

Eq. (6) in combination with Eqs. (3) and (4), which relates the electrical conductivity and degree of saturation, is fit to the experimental data. The results of the regression analysis are summarized in Table 4. The correlation coefficient R^2 is greater than 0.95 for the data. The saturation exponents are consistent with those reported in literature (Schwartz and Kimminau 1987), i.e. in the range between 1.0 and 2.5. The relationship between the normalized electrical conductivity κ_b/κ_w and degree of saturation is illustrated in Fig. 10 with a fitting curve as a function of only the degree of saturation.

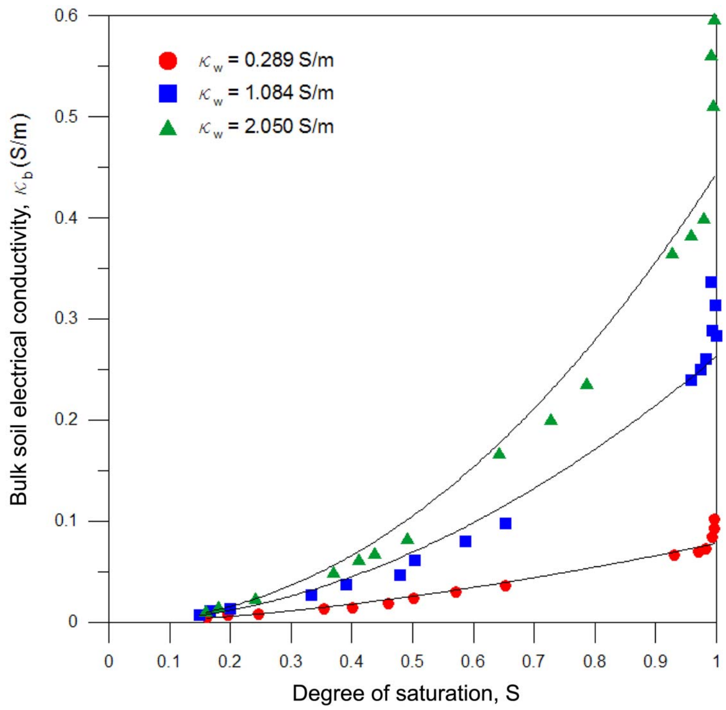


Fig. 9 Influence of degree of saturation and salinity on bulk soil electrical conductivity

Table 4 Calculated values of the empirical constants using Eq. (6)

Expression	No. of samples	c	m	p	R^2
$\kappa_b/\kappa_w = n^m S^p$ from Archie model	47	–	2.27	1.93	0.99
$\kappa_b/\kappa_w = cn^m S^p$ from Winsauer model	47	0.62	1.52	1.90	0.95

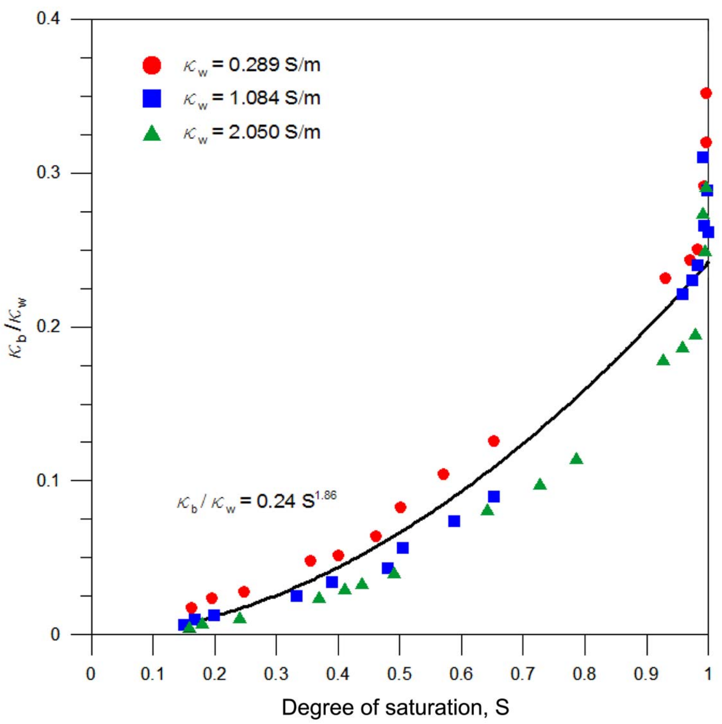


Fig. 10 Relationship between κ_b/κ_w and degree of saturation

4.4 Effect of volumetric water content

The influences of the soil volumetric water content and pore water salinity on the bulk soil electrical conductivity are examined. As plotted in Fig. 11, the experimental results indicate that the bulk soil electrical conductivity increases with increasing the volumetric water content. On the other hand, it is observed that the electrical behaviors are sensitive to the pore water salinity.

The surface electrical conductivity can be theoretically determined by extrapolating the fitting line between the bulk soil electrical conductivity and volumetric water content. However, better determination of surface electrical conductivity can be obtained by arbitrarily selecting the values (20, 30, 40, and 50%) of volumetric water content and estimating bulk soil electrical conductivities corresponding with different pore water salinities at the same volumetric water content (Kalinski and Kelly 1993). This is illustrated in Fig. 12, in which the surface electrical conductivities are estimated as the intercepts of linear regression lines. The results reveal that the surface electrical conductivity ranges from 0.007 S/m to 0.027 S/m, which are comparable to that of clayey soils in work of Shang *et al*. (1993), and Hamed *et al*. (2003). It means that the surface electrical

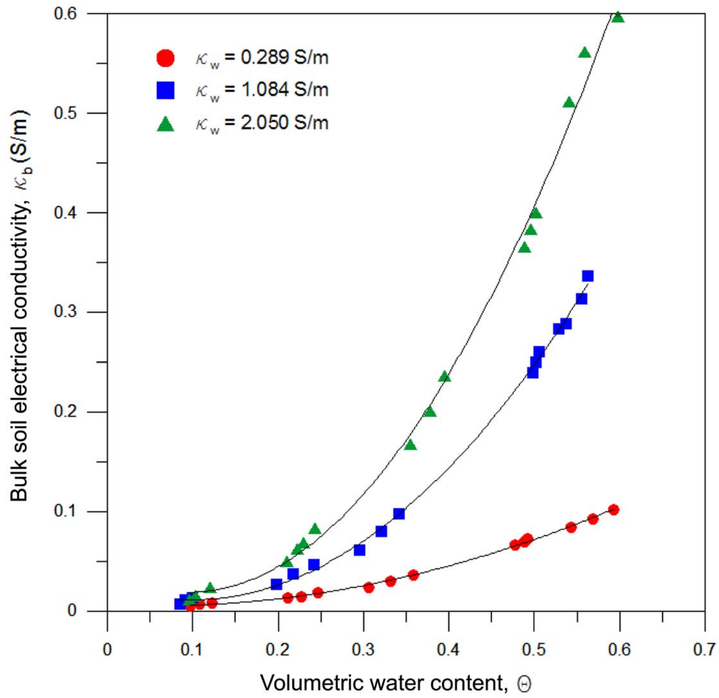


Fig. 11 Influence of volumetric water content and salinity on bulk soil electrical conductivity

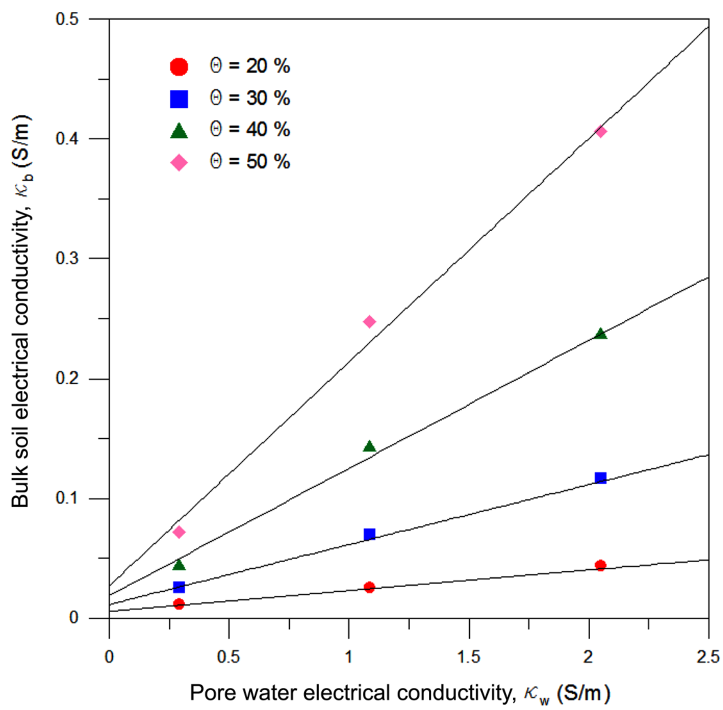


Fig. 12 Variation of bulk soil electrical conductivity against salinity for different volumetric water contents

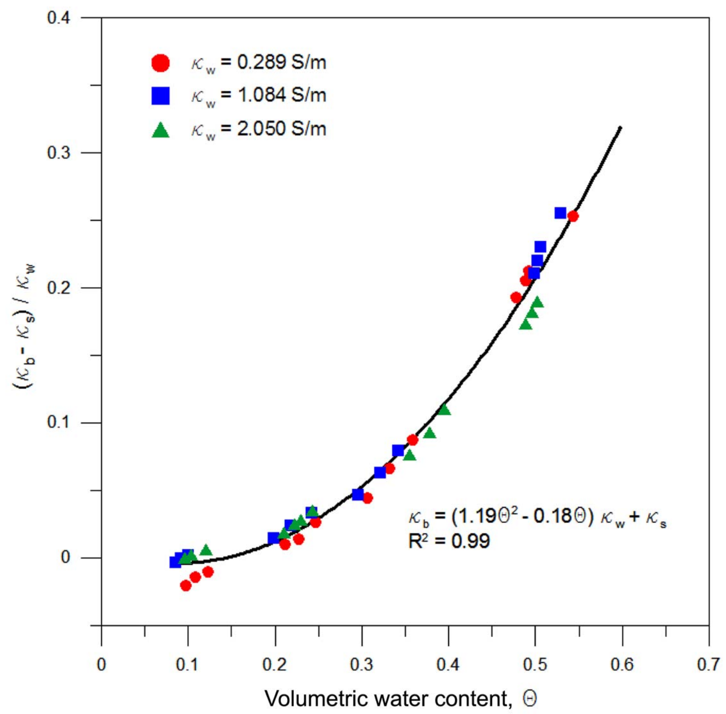


Fig. 13 Relationship between $(\kappa_b - \kappa_s)/\kappa_w$ and volumetric water content

conductivity is not constant but depends on the amount of water content in soils.

The best relationship between the normalized electrical conductivity $(\kappa_b - \kappa_s)/\kappa_w$ and soil volumetric water content is obtained by Eq. (7) using the surface electrical conductivity of κ_s = 0.011 S/m, and is illustrated in Fig. 13. The relation (R^2 = 0.99) can be expressed as

$$\kappa_b = (1.19\theta^2 - 0.18\theta)\kappa_w + 0.011 \quad (10)$$

It is shown in the figure that Eq. (10) gives good estimates of electrical behavior for kaolin clay investigated despite using a fixed value of κ_s. Kalinski and Kelly (1993) and Hamed *et al.* (2003) have also noted that the Rhoades model provides accurate approximations of soil electrical conductivity for a wide range of soils.

In order to estimate the parameters in Eq. (8), which is the generalized Archie model as a function of the volumetric water content, the relationship between the normalized electrical conductivity κ_b/κ_w and volumetric water content is established and is plotted in Fig. 14. The regression equation has the form of (R^2 = 0.95)

$$\kappa_b/\kappa_w = 0.79\ \theta^{1.91} \quad (11)$$

In this figure, the model proposed by Shah and Singh shows its limitations for kaolin clay tested due to neglecting the surface conductance effect, although they assumed that this effect will be appropriately included in the model using two empirical constants.

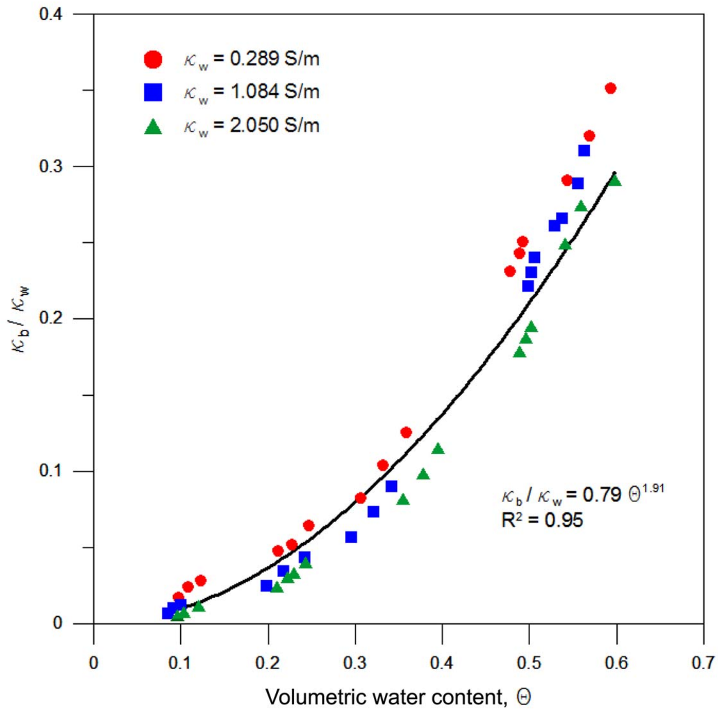


Fig. 14 Relationship between κ_b/κ_w and volumetric water content

5. Conclusions

The electrical conductivity of kaolin clay was measured using a circular two-electrode cell in conjunction with a specially designed compaction apparatus. The influences of porosity, unit weight, water content and pore water salinity on the soil electrical conductivity were investigated. The following conclusions can be drawn from this study:

(1) The formation factors of saturated kaolin clay follow both the Archie model and Winsauer models.

(2) Based on the experimental data reported and measured for saturated soils, the two general relationships according to both of the Archie and Winsauer models are established, which are useful for understanding electrical conduction characteristics of soils over a wide porosity range. With known formation factor, the soil porosity can be estimated, which forms a background against actual soil porosity.

(3) The tortuosity calculated from the measured formation factor decreases with increasing the soil porosity. Estimate of the tortuosity, reflecting the complexities of soil fabric, enables one to comprehend the mechanisms of hydraulic flow and electrical current.

(4) In unsaturated kaolin clay, the prediction models for the soil electrical conductivity are evaluated with calculated the empirical constants in these models (Table 4, and Eqs. (10) and (11)). Among the models analyzed, the Rhoades model is shown to be the best fit for the kaolin clay investigated comparing to other models.

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