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ORIGINAL ARTICLE

Estimation of soil weathering degree using electrical resistivity

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Abstract In this study, the electrical resistivity of soil having different chemical weathering index (CWI) was measured, and the correlation between CWI and the electrical resistivity was estimated. The electrical resistivity of soil varies with CWI of soil. The difference in the electrical resistivities of soils having different weathering degrees is clear at lower water contents. At the volumetric water contents estimated in this study, CWI could be described by a linear equation of electrical resistivity with the constants related to the volumetric water content. The findings in this study suggest that the electrical resistivity could be used as an effective alternative for estimating the weathering degree of soil.

Keywords Electrical resistivity · Weathering degree · Volumetric water content · Weathered soil · Chemical weathering index

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Introduction

Engineering properties of weathered soil vary broadly according to their weathering degree. The mechanical behavior of weathered soil is clearly different from that of sedimentary soil, even under the similar soil structures, due to the different process of being formed. Thus, identifying the weathering degree of a soil prior to estimating its engineering properties should be essential for a successful engineering design. The methods to estimate the weathering degree include different physical and chemical approaches, which could be selected depending on the purpose and application of the estimation. In the field, *N* value from the standard penetration test has been typically used for estimating the weathering degree. However, the *N* value could contain substantial error due to the discontinuity of soil layer in the field and the possibility of mistakes being made by the field engineer.

Laboratory testing of the soil sample collected from the field is more generally used these days rather than the direct use of the *N* value from field testing. Mineral composition and structural changes in a soil have been used for estimating the weathering degree (Lumb 1962; Mendes et al. 1966; Irfan and Dearman 1978; Murata et al. 1987; Sueoka 1988; Park and Lee 1999). Some researchers have suggested the weathering index based on the resistivity to weathering or the stiffness of a soil (Irfan and Dearman 1978; Lee and Freitas 1988; Lee and Chang 2003). Iliew (1966) proposed an equation relating the weathering degree with the velocity of elastic wave through the soil medium. Among the various laboratory methods proposed so far, chemical weathering index (CWI), proposed by Sueoka (1988), is currently popularly used in geological and geotechnical engineering field to describe the weathering degree of a soil. Sueoka (1988) conducted an analysis on the chemical composition of a soil and used the ratio of certain chemical contents, which are sensitive to weathering, to total chemical contents as a weathering index. Although CWI could give a reliable weathering index for a soil, it requires a relatively long time and high cost for the analysis. Therefore, simple, rapid and cost-effective alternative need to be developed to estimate the weathering degree of a soil.

The electrical property of the soil has been proposed as an alternative index to estimate the contamination of a soil for its time and cost-effectiveness. In previous studies (Keller and Frischknecht 1966; Parkhomenko 1967; Arulanandan and Muraleetharan 1988; Ward 1990; Thevanayagam 1993; Yoon and Park 2001), the electrical resistivity was found to be affected by the porosity, the electrical resistivity of pore fluid, the saturation degree and the pore structure of a soil medium. Purvance and Andricevic (2000) presented a positive relationship between hydraulic conductivity and electrical conductivity of porous rocks. Especially, Abu-Hassanein et al. (1996) and Yoon and Park (2001) reported that the soil composition could change the electrical resistivity appreciably, which implied that the electrical resistivity of a soil might be used as an alternative index for representing the weathering degree of a soil. As far as we know, currently there is no study that estimates the relationship between the weathering degree and the electrical resistivity of a soil.

In this study, the electrical resistivity was evaluated as an alternative for measuring the weathering degree of a soil. CWI was employed as a standard index representing the weathering degree of the soil estimated. The electrical resistivity of a soil at different weathering degrees was measured, and the relationships between CWI and electrical resistivity were estimated. Also, based on the tests of different water content, the optimum condition for estimating the weathering degree of a soil with electrical resistivity was proposed.

Materials and testing methods

Materials

The properties of soils used in this study are summarized in Table 1. The soils, titled H, were collected from Hwaseong, Gyeong-gi province in Korea and the soil, titled L, from Ilsan, Gyeong-gi province in Korea. The soils, having different weathering degrees, were collected from each site.

Testing methods

The soil sample was prepared, by mixing with water, to have pre-determined water contents (0, 5, 10, 15, 20 and 25%). The prepared soil was packed into the acrylic mold, which was specially designed for measuring the electrical resistivity of the soil specimen (Fig. 1).

The mold has the dimension of 15 cm × 2 cm × 20 cm. Electrical resistivity of the soil was measured by using HP4285A Precision LCR meter (Hewlett-Packard, USA) and Agilent 4263B LCR meter (Agilent, USA). HP4285A LCR meter is generally available for the frequency range of 75 kHz–30 MHz, and Agilent 4263B LCR meter for 100 Hz–100 kHz. At each measurement, the electrical frequency was varied from 100 Hz to 10 MHz.

Preliminary test was conducted for estimating the effect of electrolytes in pore water on the electrical resistivity of

Table 1 Physical properties of soils

Soils	Sampling depth (m)	Specific gravity (G_s)	Liquid limit (%)	Plasticity index (%)	USCS
H-1	1.0	2.75	–	NP	SM
H-2	2.0	2.73	–	NP	SM
H-3	3.0	2.72	–	NP	SM
H-4	1.0	2.68	–	NP	SM
L-1	4.5	2.66	–	NP	SM
L-2	6.7	2.67	–	NP	SM
L-3	7.5	2.70	–	NP	SM
L-4	9.5	2.69	–	NP	SM

USCS Unified soil classification system

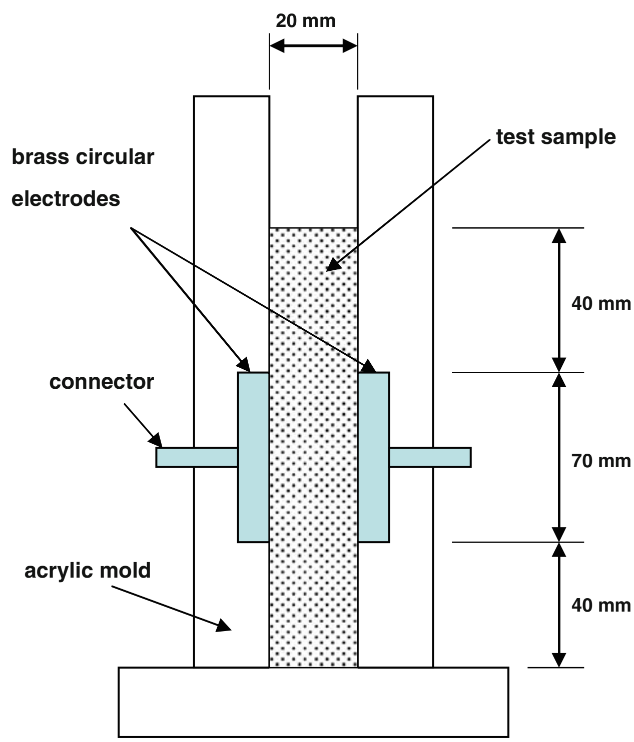

Fig. 1 Acrylic mold used for measuring electrical resistivity of soil

Table 2 Results of XRF analysis for H and L soils (%)

Soils	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	L.O.I	CWI
H-1	62.26	16.15	0.77	8.55	1.89	0.31	0.60	1.90	0.11	0.07	4.03	28.44
H-2	60.42	16.70	0.98	9.27	2.68	1.51	0.91	0.99	0.12	0.14	5.36	32.05
H-3	63.26	17.12	0.80	7.81	1.99	0.76	1.31	1.82	0.11	0.07	3.84	27.52
H-4	59.66	16.02	0.76	8.64	1.88	0.58	0.46	1.30	0.11	0.09	5.33	32.49
L-1	63.86	16.97	0.75	8.23	1.20	0.69	1.08	1.65	0.03	0.06	4.66	29.88
L-2	70.49	13.66	0.52	6.67	0.69	0.20	1.06	2.54	0.11	0.06	3.39	22.99
L-3	74.39	12.96	0.22	5.12	0.42	0.13	1.62	2.24	0.27	0.03	3.16	20.53
L-4	60.86	24.25	1.17	4.89	0.58	0.17	0.52	4.49	0.07	0.06	3.02	29.29

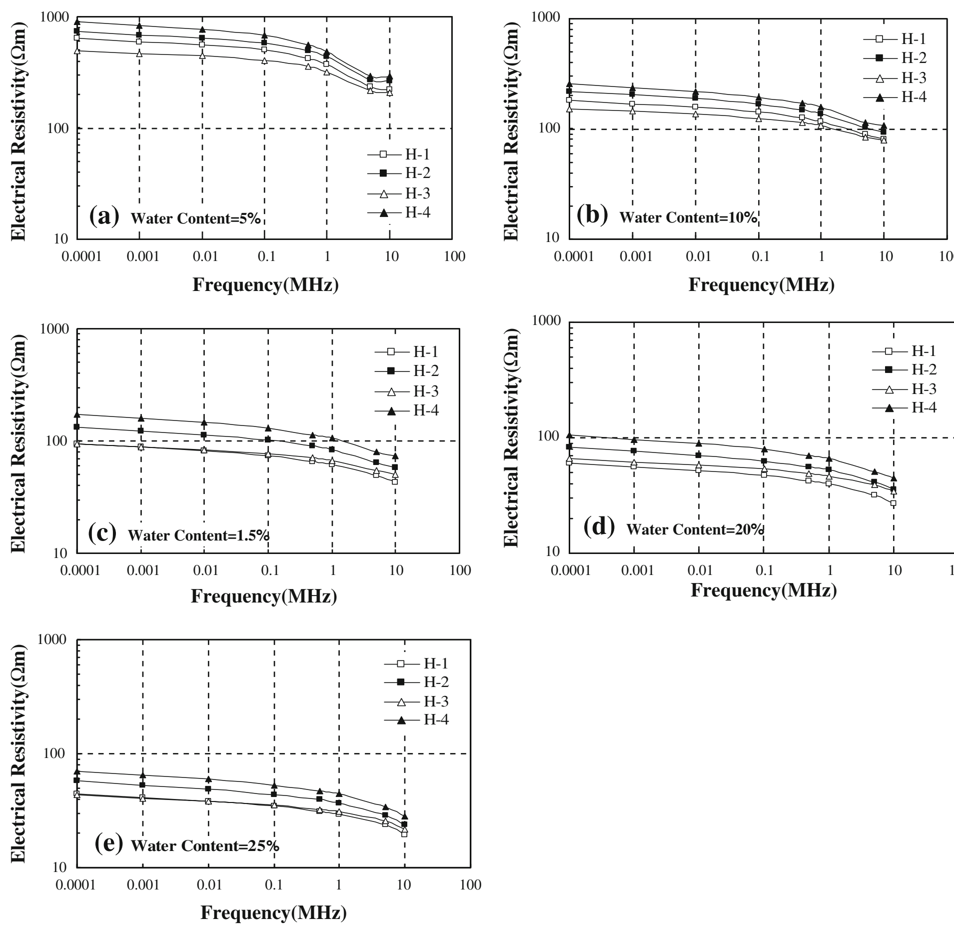

Fig. 2 Relationship between frequency and electrical resistivity against water content of H soil: **a** 5%, **b** 10%, **c** 15%, **d** 20%, **e** 25%

the specimen. Electrical resistivities of deionized water, tap water and potassium chloride (KCl) solution at the concentration 1.8 and 3.7 mM, were measured. Electrical resistivity was highest in deionized water, followed by tap water, 1.8 mM KCl solution and 3.7 mM KCl solution, which indicates that the presence of electrolyte in pore water could appreciably affect the electrical resistivity of the soil specimen. Thus, deionized water was used in this study for preparing soil specimen to eliminate the effect of electrolyte in pore water.

Chemical weathering index was used as the standard index representing the weathering degree of a soil estimated. To estimate the chemical composition of a soil, X-ray fluorescence (XRF) analysis (XRF-1700, Shimadzu, Japan) was conducted. CWI was calculated by Eq. 1 as suggested by Sueoka (1988):

$$\mathrm{CWI} = \left(\frac{\mathrm{Al_2O_3 + Fe_2O_3 + TiO_2 + L.O.I.}}{\text{All chemical components}}\right)_{\text{mole}} \times 100(\%) \quad (1)$$

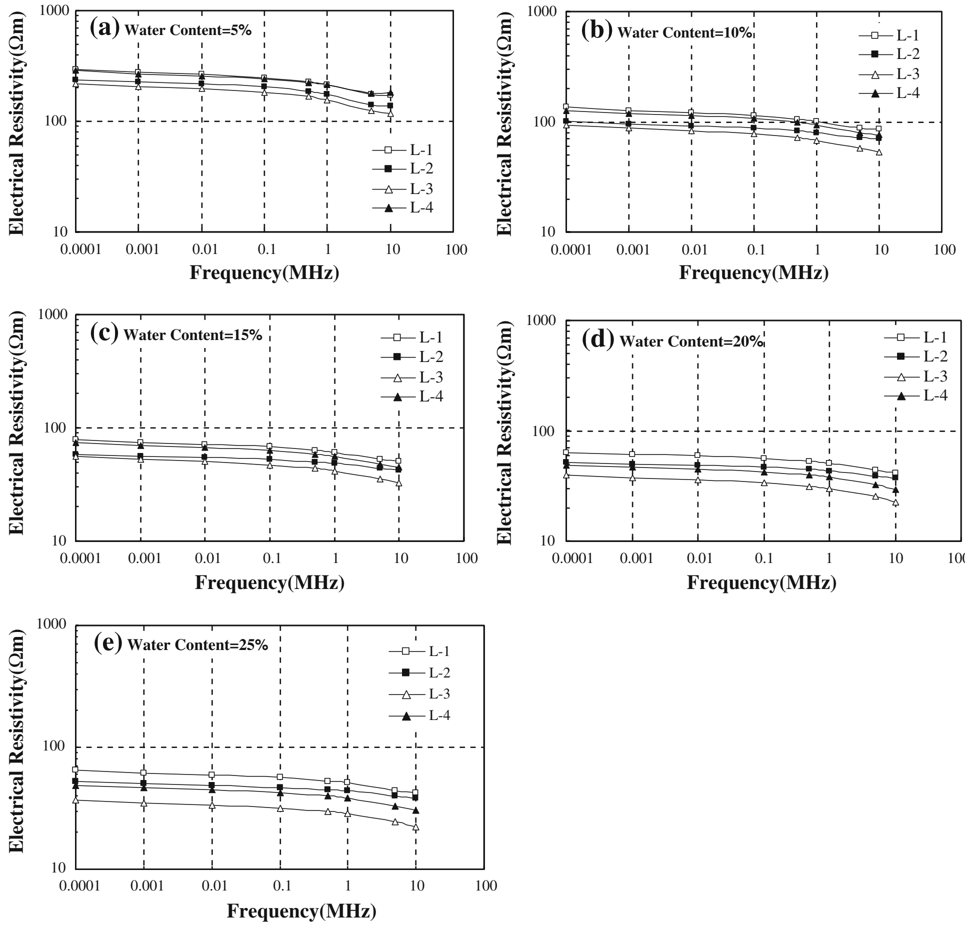

Fig. 3 Relationship between frequency and electrical resistivity against water content of L soil: **a** 5%, **b** 10%, **c** 15%, **d** 20%, **e** 25%

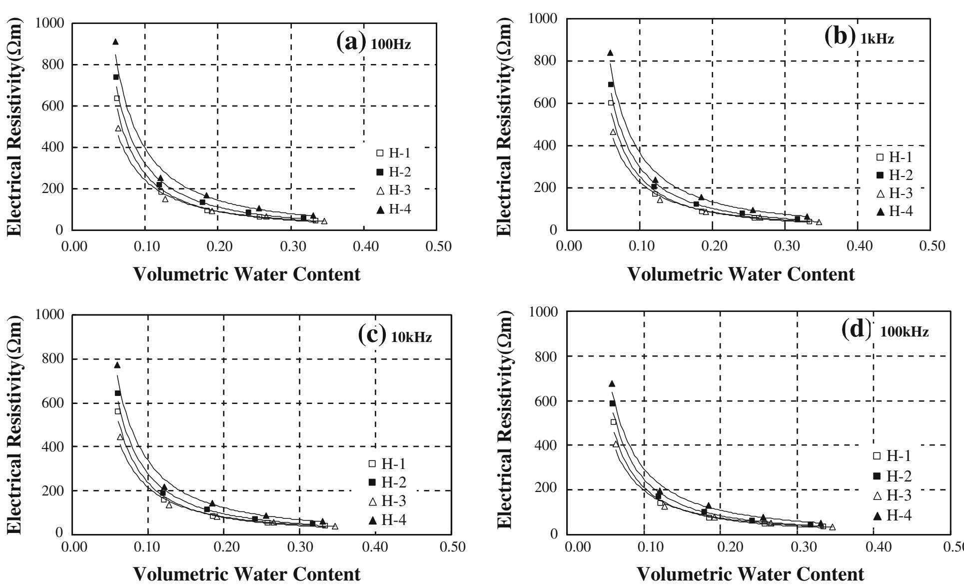

Fig. 4 Trend lines of relationship between volumetric water content and electrical resistivity of H soil: **a** 100 Hz, **b** 1 kHz, **c** 10 kHz, **d** 100 kHz

Results and discussion

The chemical compositions of soils and the resulting CWIs are summarized in Table 2. H soils generally show higher weathering degree than L soils, but no significant relationship between the sampling depth and the weathering degree is found. However, the soil collected at each site shows different weathering degree, ranged broadly enough to compare the difference.

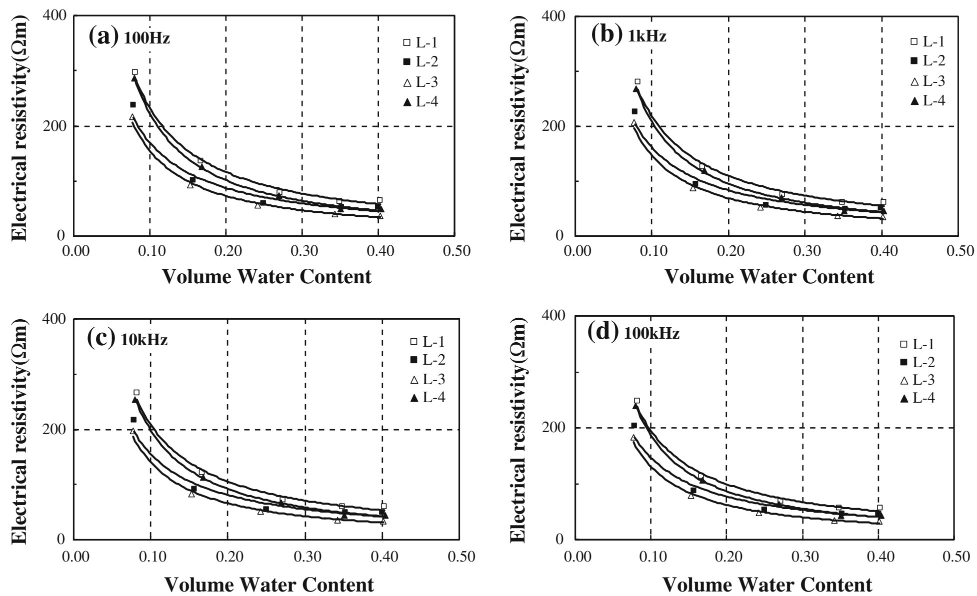

Fig. 5 Trend lines of relationship between volumetric water content and electrical resistivity of L soil: **a** 100 Hz, **b** 1 kHz, **c** 10 kHz, **d** 100 kHz

Table 3 Regressive equations of electrical resistivity vs. volumetric water content of H soil

Frequency	Soils	$\rho = a\theta^b$		
		a	*b*	R^2
100 Hz	H-1	7.18	−1.579	0.9934
	H-2	9.54	−1.527	0.9958
	H-3	9.82	−1.390	0.9926
	H-4	14.13	−1.446	0.9911
1 kHz	H-1	6.57	−1.587	0.9933
	H-2	8.75	−1.534	0.9959
	H-3	9.04	−1.402	0.9930
	H-4	13.08	−1.447	0.9918
10 kHz	H-1	6.08	−1.591	0.9931
	H-2	7.97	−1.542	0.9957
	H-3	8.44	−1.407	0.9929
	H-4	11.98	−1.448	0.9922
100 kHz	H-1	5.57	−1.582	0.9932
	H-2	7.05	−1.549	0.9952
	H-3	7.82	−1.404	0.9928
	H-4	10.75	−1.441	0.9925

ρ Electrical resistivity (ohm meter), θ volumetric water content, *a*, *b* dimensionless

Table 4 Regressive equations of electrical resistivity vs. volumetric water content of L soil

Frequency	Soils	$\rho = a\theta^b$		
		a	*b*	R^2
100 Hz	L-1	23.17	−1.001	0.9854
	L-2	18.61	−0.960	0.9577
	L-3	12.69	−1.086	0.9926
	L-4	16.33	−1.135	0.9936
1 kHz	L-1	22.33	−0.990	0.9847
	L-2	18.05	−0.952	0.9547
	L-3	11.88	−1.092	0.9915
	L-4	15.743	−1.121	0.9938
10 kHz	L-1	21.74	−0.981	0.9845
	L-2	17.73	−0.942	0.9541
	L-3	11.45	−1.088	0.9912
	L-4	15.32	−1.111	0.9938
100 kHz	L-1	20.78	−0.971	0.9842
	L-2	17.31	−0.927	0.9539
	L-3	10.87	−1.079	0.9909
	L-4	14.59	−1.106	0.9937

ρ Electrical resistivity (ohm meter), θ volumetric water content, *a*, *b* dimensionless

Effect of water content and frequency on the electrical resistivity of soil

The electrical resistivity of soil was measured at different water contents by varying the frequency from 100 Hz to 10 MHz. The results for H and L soils are presented in Figs. 2 and 3, respectively. In general, electrical resistivity decreases with increasing water content (Figs. 2, 3).

Electrical resistivity is higher in the soil with higher CWI, which is clear at lower water content (Figs. 2a, b, 3a–c). At higher water content, the discrepancy in the electrical resistivities of soils becomes smaller or negligible. This indicates that the electrical resistivity of soil specimen might be governed by pore water rather than by the properties of soil at above certain level of water content.

Electrical resistivity of a given soil slightly decreases up to approximately 100 kHz and thereafter it significantly

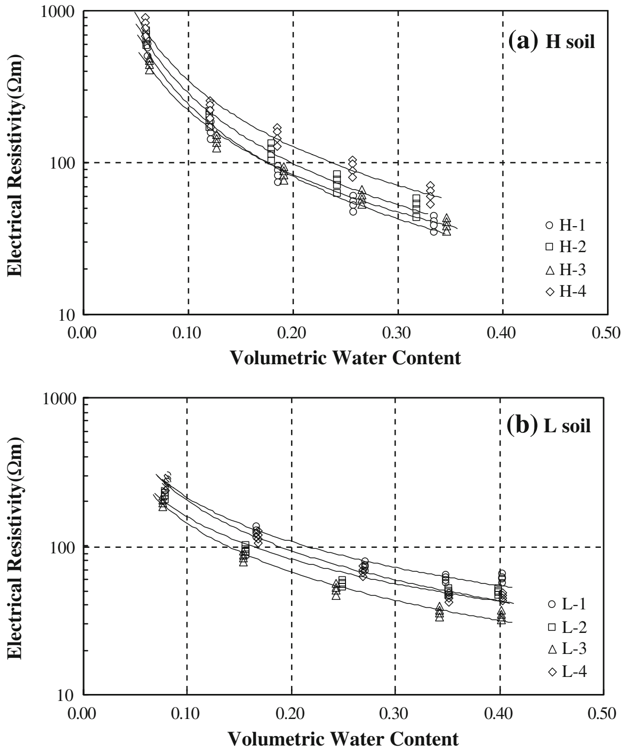

Fig. 6 Relationship between electrical resistivity and volumetric water content of all samples: **a** H soil, **b** L soil

Table 5 Regressive equations of electrical resistivity vs. volumetric water content

Soils	$\rho = a\theta^{b}$		
	a	*b*	R^2
H-1	6.32	−1.585	0.9841
H-2	8.28	−1.538	0.9841
H-3	8.75	−1.401	0.9849
H-4	12.42	−1.446	0.9780
L-1	21.99	−0.986	0.9753
L-2	17.92	−0.945	0.9491
L-3	11.70	−1.086	0.9831
L-4	15.48	−1.118	0.9862

ρ Electrical resistivity (ohm meter), θ volumetric water content, *a*, *b* dimensionless

decreases with frequency. This is called the relaxation behavior and it is due to the dynamic effects of polarization, which are affected by frequency (Santamarina et al. 2001; Oh et al. 2007). In general, the dynamic effects of polarization on resistivity measurement are not significant at frequencies below 100 kHz (Rinaldi and Cuestas 2002). Thus in the following analysis, frequency was varied only up to 100 kHz to eliminate the relaxation effect.

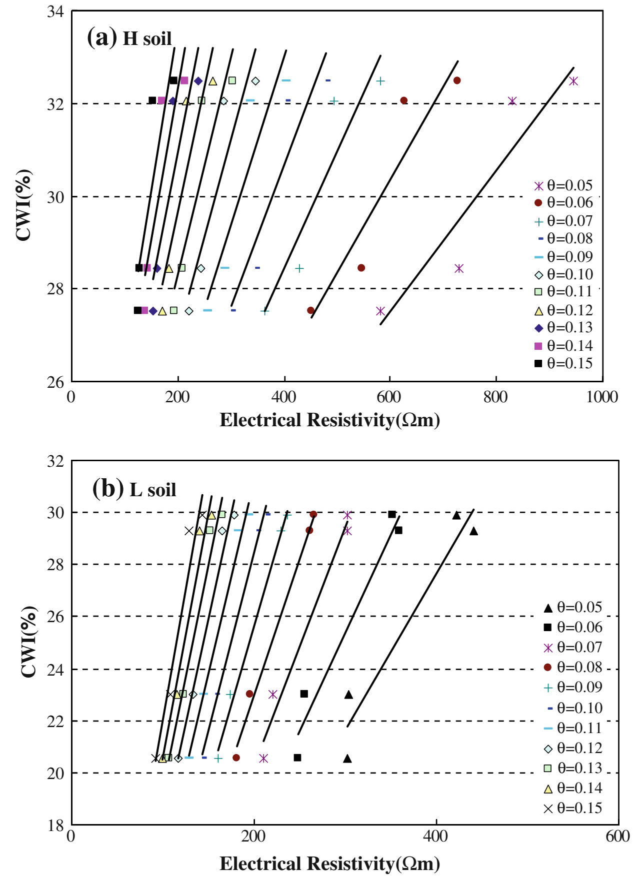

Fig. 7 Relationship between CWI and electrical resistivity: **a** H soil, **b** L soil

Correlation between volumetric water content and weathering degree

To consider the combined effect of gravimetric water content and dry density (γ_d) of soil specimen on the electrical resistivity, the volumetric water content of soil specimen was calculated and correlated with electrical resistivity. The relationships between volumetric water content and electrical resistivity for H soils and L soils are shown in Figs. 4 and 5, respectively. The non-linear regression equations for these relationships are summarized in Table 3 for H soils and in Table 4 for L soils.

At lower volumetric water content, the differences in the electrical resistivities of soils having different CWIs are clear; that is, the electrical resistivity is higher in the soil with higher CWI, which is consistent with the results shown in Figs. 2 and 3. However, at higher volumetric water content, the electrical resistivities of soils even having different weathering degree (CWIs) become similar and therefore difficult to be differentiated. At the frequency applied, the difference in electrical resistivity of L soil (up to 0.20) is maintained relatively clearly than that of H soil (up to 0.15) in the higher volumetric water content.

Table 6 Regressive equations of CWI vs. electrical resistivity

Soil	Volumetric water content (θ)	CWI = $\alpha \cdot \rho + \beta$		
		α	β	R^2
H soil	0.05	0.015	18.35	0.8772
	0.06	0.020	18.29	0.8829
	0.07	0.025	18.33	0.8807
	0.08	0.031	18.42	0.8737
	0.09	0.036	18.55	0.8638
	0.10	0.0421	18.71	0.8521
	0.11	0.047	18.87	0.8395
	0.12	0.053	19.04	0.8264
	0.13	0.059	19.21	0.8131
	0.14	0.065	19.38	0.7999
	0.15	0.071	19.55	0.7869
L soil	0.05	0.060	3.55	0.9319
	0.06	0.076	2.68	0.9621
	0.07	0.091	2.10	0.9808
	0.08	0.106	1.73	0.9911
	0.09	0.121	1.52	0.9952
	0.10	0.135	1.44	0.9946
	0.11	0.149	1.45	0.9906
	0.12	0.163	1.53	0.9841
	0.13	0.176	1.66	0.9757
	0.14	0.188	1.83	0.9659
	0.15	0.201	2.03	0.9552

CWI chemical weathering index (%), ρ electrical resistivity (ohm - meter), α, β dimensionless

Since the constants in the regression equations (Tables 3, 4) did not vary largely for the frequency applied, one representative regression equation was prepared for each soil sample (Fig. 6). The equations for the regression curves in Fig. 6 are summarized in Table 5.

Table 7 Regressive equations of co-efficient (α, β) vs. volumetric water content (θ) of all samples

Soil	Regressive equation	R^2
H soil	$\alpha = 0.56\theta - 0.014$	0.9992
	$\beta = 97.2\theta^2 - 6.2\theta + 18.34$	0.9907
L soil	$\alpha = 1.41\theta - 0.008$	0.9986
	$\beta = 539.7\theta^2 - 119.6\theta + 7.98$	0.9630

Using the equations in Table 5, the electrical resistivity of a soil at a certain volumetric water content was calculated and related to CWI of the soil (Fig. 7). The equations for regressive lines shown in Fig. 7 are summarized in Table 6.

Due to the increasing effect of pore water on electrical resistivity at higher water content, the volumetric water contents in the range of 0.05–0.15 were considered for the estimation.

At the volumetric water content within the ranges estimated, the electrical resistivity of a soil show linear relationship with CWI of that soil (Fig. 7) as:

$$\mathrm{CWI}(\%) = \alpha \cdot \rho + \beta \quad (2)$$

where ρ is the electrical resistivity (ohm meter) and α and β are constants.

For H soils, α is in the range of 0.015–0.071 and β in the range of 18.29–19.55. For L soils, α is in the range of 0.06–0.201 and β in the range of 1.44–3.55. The constant of α increases with the volumetric water content, while β decreases initially, but increases thereafter as the volumetric water content increases (Table 6). The relationship

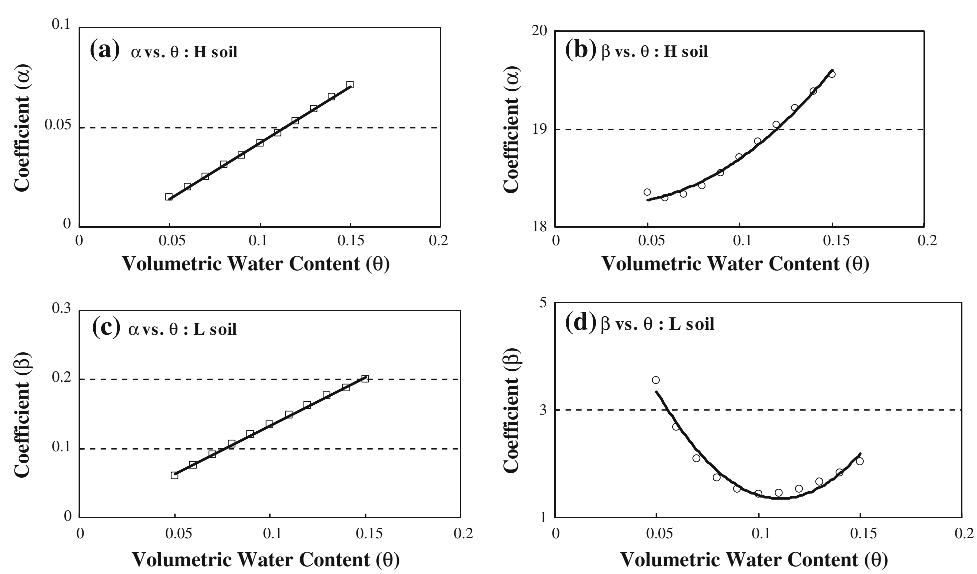

Fig. 8 Relationship between volumetric water content and co-efficient α, β: **a** α vs. θ of H soil, **b** β vs. θ of H soil, **c** α vs. θ of L soil, **d** β vs. θ of L soil

between the constants of α and β and the volumetric water content is shown in Fig. 8, and summarized in Table 7.

At the given volumetric water content, the constants of α and β in Eq. 2 could be calculated using the relationship in Table 7. Thus, CWI could be calculated by measuring the electrical resistivity of soil.

Summary and conclusions

In this study, the electrical resistivity was evaluated as a simple, rapid and cost-effective alternative for estimating the weathering degree of soil. The electrical resistivity of soil sample varies with the weathering degree of the soil. The difference in the electrical resistivities of soils having different weathering degrees is clear at lower water contents. At the volumetric water contents in the range of 0.05–0.15, CWI could be described by a linear relationship with the electrical resistivity $(\mathrm{CWI}(\%) = \alpha \cdot \rho + \beta)$. The constants of α and β in the equation are related to the volumetric water contents. Thus, at the given volumetric water content, CWI could be calculated by measuring the electrical resistivity of soil and using the empirical relation between the volumetric water content and the constants. However, the constants which might include the uncertainties in the measurements need to be refined by accumulating more data at different conditions to increase their reliability.

The findings from this study suggest that the electrical resistivity could be used as an effective alternative for estimating the weathering degree of soil.

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