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Sensitivity of leachate and fine contents on electrical resistivity variations of sandy soils

Gil Lim Yoon [a,*], Jun Boum Park [b]

[a] *Korea Ocean Research and Development Institute (KORDI), Coastal and Harbor Research Laboratory, Ansan 425-744, South Korea*

[b] *School of Civil, Urban, and Geosystem Engineering, Seoul National University, Seoul, South Korea*

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Abstract

Laboratory pilot tests were performed to investigate the relationship between electrical resistivity and contaminated soil properties. Three different sandy soils and leachate collected from one of the industrial waste landfill sites in Korea were mixed to simulate contaminated soil conditions. The values of electrical resistivity of the soils were measured using laboratory scaled resistivity cone penetrometer probe. In the experiments, electrical resistivity was observed in terms of water content, unit weight, saturation degree of the soils, and leachate concentration. The experimental results show that the electrical resistivity of the sandy soils depends largely on the water content and electrical properties of pore water rather than unit weight and types of soils. The amount of fines can have significant effect on electrical properties of soils. Direct correlation with contamination in such soils may not be valid here. The results suggest that the electrical resistivity measurement is well suited and applicable for monitoring and delineation of contaminants in the subsurface. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Electrical resistivity; Leachate; Heavy metal; Clay minerals; Water content; Soil contamination

1. Introduction

For an effective approach of contaminated site remediations, the United States Environmental Protection Agency [1] noted the site specific requirements for in both physical properties and chemical characterization of the ground: (i) stratigraphy; (ii) groundwater-level data; (iii) hydraulic conductivity and (iv) chemical distributions and sources/receptor for potential contaminants.

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[*] Corresponding author. Fax: +82-31-408-5823.

E-mail address: glyoon@kordi.re.kr (G.L. Yoon).

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As indicated, the evaluation of the ground conditions such as groundwater and soil properties has become increasingly important for site characterization, when more industrial wastes and domestic solid refuse come into contact with groundwater and soils. One of the emerging techniques to efficiently assess the subsurface contamination is to examine the contaminated media using geophysical methods. One geophysical method is an electrical resistivity measurement, which can be performed rapidly and nondestructively in situ.

The electrical resistivity of the soil is, amongst other factors, dependent on soil type, degree of saturation, concentration of ions, and temperature of pore water. Properties that affect the resistivity of a soil or rock also include porosity, water content, composition, salinity of the pore water, grain size distribution, and particle shape and orientation [2,3]. Every soil type possesses a natural conductivity within certain limits; deviations may suggest possible pollution. It is known that contaminants influence the bulk resistivity of soil, because they change the electrical properties of the groundwater and soils [4,5].

From the laboratory model investigation experience, it was found that the presence of fines in a sandy soil affects the resistivity in two ways: (1) increased fines content will decrease porosity, which has the effect of increasing the resistivity and (2) the presence of fines in the soil may indicate the presence of conducting clay minerals, which would result in a decrease in the resistivity. In clay soils, electrical conduction occurs in the pores and on the surfaces of electrically charged clay particles [6,7]. For clays, surface conductance can be a significant factor affecting the bulk electrical resistivity of the soil [2].

Although, quantitative correlation between electrical resistivity measured by a cone penetrometer and concentration of contaminant in the subsurface has not been fully established, electrical resistivity measurement can give a fairly good quantitative indication of the plume distribution. Bernstone and Dahlin [9] successfully delineated the extent of two capped Swedish landfills using dc resistivity surveying in both plane and approximately in depth, and displayed contaminated geological structures. Also, the difficulty is identifying which components cause changes in the resistivity [10,11]. Yoon et al. [12] also investigated the leachate distribution of a landfill site located in southern part of Korea near the city of Chonju using geophysical techniques such as electrical resistivity measurement and georadar reflection. They successfully delineated the landfill site down to 25 m in three-dimensional configuration. Darayan et al. [13] provided a basis for using ground-penetrating radar or other high-frequency electromagnetic sensors in the detection of soil contamination by measuring both the dielectric constant and the electrical conductivity (EC) of the contaminated soils.

Electrical resistivity method can be successfully used for the geotechnical applications as well as for detecting the contaminated plume in the subsurface. Abu-Hussanein et al. [4,5] determined the bentonite content in soil–bentonite mixtures using electrical resistivity. Kalinski et al. [14] evaluated the hydraulic conductivity of compacted soil liners of the landfill with electrical resistivity measurement. They concluded that high resistivity might be indicative of low molding water content, high air-filled porosity, or high sand or gravel content on the material scale. On the liner scale, resistivity measurements might be useful for identifying desiccation cracking or poor interlift bonding. EC was also properly used for determining chemical equilibrium in laboratory compatibility tests involving permeation with electrolyte solutions by EC breakthrough curves [15]. Measured data showed that the magnitude of the EC in the soil due to the existence of soluble salts relative to the EC of the permeant liquid affected significantly the observed shapes of the EC breakthrough curves.

As the factors affecting electrical resistivity of soils are very important for the characterization of contaminated subsurface, parametric studies based on laboratory-scaled pilot experiments between electrical resistivity and contaminated soil properties have been performed in this research.

2. Electrical resistivity measurement method

The electrical resistivity of the soil is determined by measuring the resistance of the soil. This is done by measuring the voltage across a pair of electrodes at a known current level. However, the measured resistance is not a unique material property. The resistance is proportional to the length and the inverse of the cross-sectional area, of the electrical conducting material being measured. Resistivity (ρ) can be defined as following equation.

$$R = \left(\frac{L}{A}\right)\rho \tag{1}$$

where R is resistance (Ω), A cross-sectional area (m^2) and L length (m).

For the case of a pair of electrodes in a homogeneous, isotropic conducting media there is a linear relationship between resistance and resistivity as given in Eq. (2).

$$\rho = KR \tag{2}$$

where K is constant, being a function of the geometry of the electrode pair.

The electrical resistivity method works on the principal that the measured voltage drop across a pair of electrodes at a certain current is proportional to the electrical resistivity of the soil. In an electrically conductive body that lends itself to description as a one-dimensional body, Ohm's law describes the relationship between the current and potential distribution. Resistivity (ρ) is equal to the reciprocal of conductivity (C) as given in Eq. (3).

$$C\ (\mathrm{mS/m}) = \frac{1000}{\rho\ (\Omega\,\mathrm{m})} \tag{3}$$

All materials, including soil and rock, have an intrinsic property of resistivity, which governs the relationship between the current density and the gradient of the electrical potential. There are many different kinds of electrical resistivity measurement systems, which are depending on current and electrode array system. Typical measurement system includes Wenner type, Schlumberger type and Lee-partitioning system. It is known that the spacing between electrodes in the measuring system also affect resistivity measurements of the soil [16]. Keller and Frischknecht [17] demonstrated that approximately 90% of the injected current flows through depths less than the electrical resistivity measurement probe spacing L and that distance can be practically assumed to the depth of observation. For a field liner, the distance L can be the thickness of a single lift, a specified number of lifts, or the total liner, depending on the desired depth of observation.

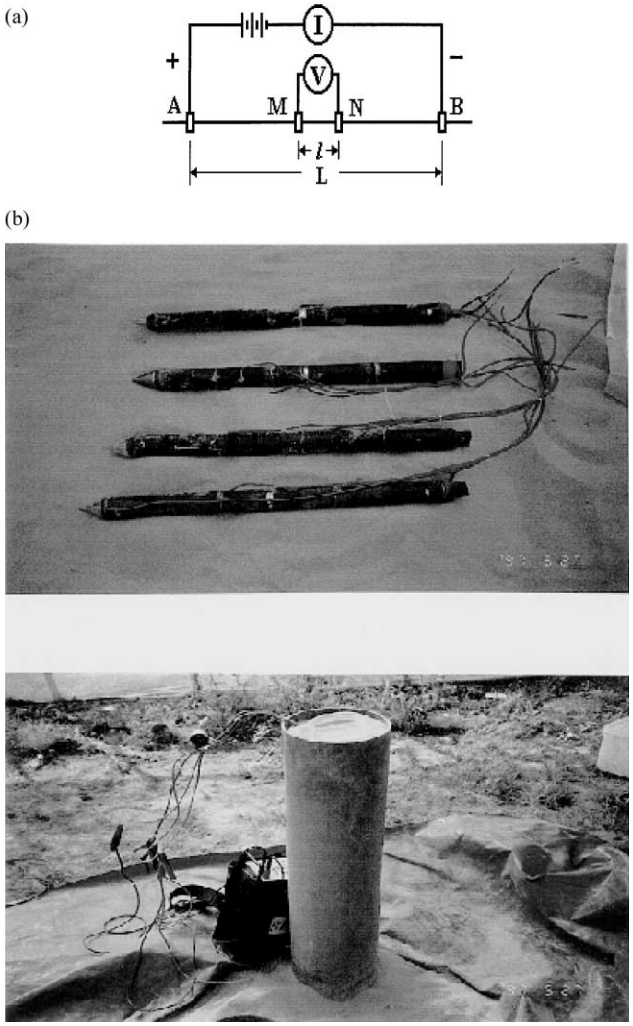


Fig. 1. (a) Typical Schlumberger electrode array system; (b) four different electrode distance dummy cone (above) and PVC circular chamber for measuring resistivity of test soils (below).

In this experiment, test results of Schlumberger array type resistivity system was only used to investigate relationships between contaminated soils and electrical resistivity (Fig. 1a). Details on resistivity difference between Wenner system and Schlumberger array system are described by Yoon et al. [12]. A four-electrode array, where measurements are only made with the inner electrodes, minimizes the effect of polarization, since the current drawn through the measurement electrodes is very small, so there is no appreciable build-up of ions at the electrodes [10]. Fig. 1b shows the pictures of dummy-cone used in this study and circular chamber for measuring resistivity of test soils. Details on electrode array system are also described by Thevanayagam [18].

Table 1
Physical characteristics of the test soils[a]

Soils	G_s	Passing #200 (%)	PI (%)	W (%)	USGS
SAND	2.64	1.5	NP	16.0	SP
MASA	2.68	0.7	NP	8.1	SP
SAN-TO	2.66	7.5	NP	9.5	SP-SM

[a] G_s: specific gravity, passing #200: soils passed with 0.075 mm opening Sieve, PI: plasticity index, W: water content, USGS: unified soil classification system, SP: poorly graded sand, SP-SM: poorly graded sand and silty sand.

3. Materials and test methods

Three kinds of soils; sandy soil (SAND), weathered sandy soil (MASA) and silty sand soil (SAN-TO), commonly distributed around the Korean peninsular, were used to investigate relationship between electrical resistivity and properties of contaminated soils. The physical properties for the test soil are summarized in Table 1. Note that only SAN-TO contains 8% of silty clay particles among three sampled soils. Soil size distribution curves for the test soils are shown in Fig. 2.

Also, to simulate contaminated soil conditions, leachate sampled from industrial landfill site called 'greater city of Inchon landfill', which is one of the biggest landfills in the world (area: 195.8 km^2, landfill capacity: 280 million m^3), was added to each soil sample. The major heavy metal concentrations such as Cr, As, Cd, Pb, Cu, Hg, of the soils and leachate collected at landfill site were analyzed (Table 2(a)) before performing experiments, because the concentration of heavy metal in soils and leachate is a main factor in the resistivity measurements. The electrical resistivity of the leachate used in this experiment is measured less than one (0.5 Ω m). The inorganic species concentrations in leachate were also shown in Table 2(b). The values of BOD and COD for the leachate are 820 and 285 mg/l, respectively. Also, the pH and EC measured for the leachate are 8.76 and 23.51 mS/cm, respectively. The standard proctor test results for the test soils are shown in Table 3 and Fig. 3.

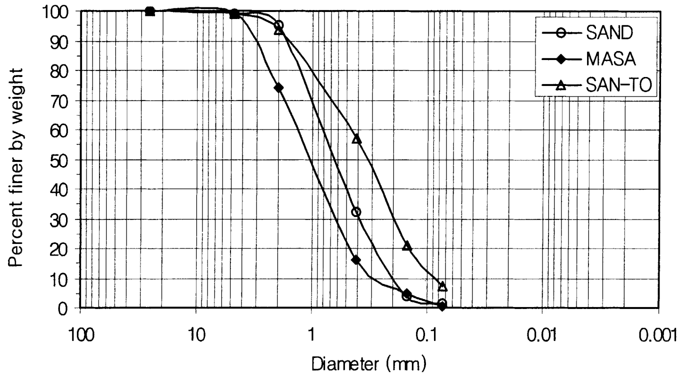


Fig. 2. Soil size distribution curves for Korean sandy soils.

Table 2
Constituents concentrations in soils and leachate

Heavy metals	SAND (ppb)	MASA (ppb)	SAN-TO (ppb)	Leachate (mg/l)
(a) Heavy metals in soils and leachate				
Cr	0.8	0.8	1.0	1.015
As	5.0	5.0	5.0	0.215
Cd	0	0	0	0.030
Pb	17.0	14.8	12.0	0.440
Cu	0	0	0	0.030
Hg	0	0.3	0	0.005

Ions	Concentrations
(b) Ion concentrations in leachate (mg/l)	
K^+	1400
Na^+	1716
NH_4^+	935
Mg^{2+}	238
Ca^{2+}	243
Fe^{2+}	26
Cl^-	4214
SO_4^-	152

Table 3
Standard proctor compaction test results

	SAND	MASA	SAN-TO
Maximum unit weight (g/cm^3)	1.67	1.91	1.89
Optimum moisture content (%)	17.70	12.6	15.90

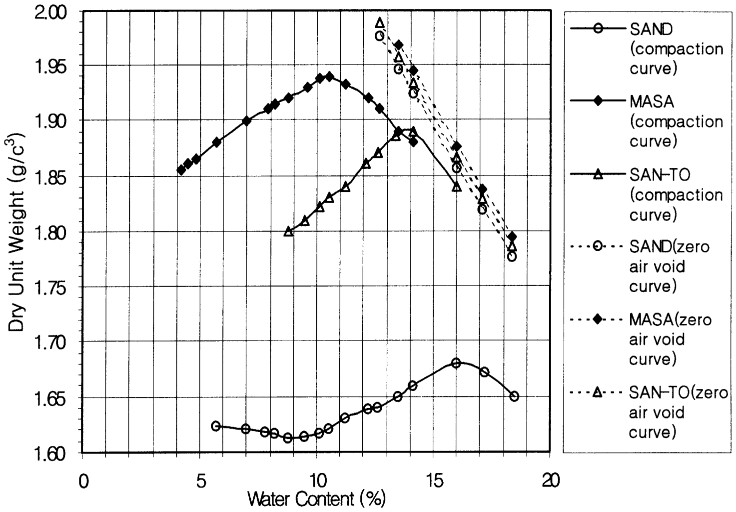


Fig. 3. Standard proctor compaction test results for the test soils.

Pilot-scaled laboratory experiments were performed using circular chamber made of polyvinylchloride (PVC), with a diameter of 500 mm and height of 700 mm (Fig. 1b). PVC chamber diameter was determined as two times electrode distance to take account of influential distance of electrolyte. STING R1/SWIFT resistivity measuring system "memory earth resistivity meter" of Advanced Geoscience Inc. was used to measure electrical resistivity of the soils. Calibration works for measuring system of different electrode distance were done before experiments with changing electrode distance of Wenner array, Schlumberger array measuring system and also calibration of the resistivity measured was made using pure water instead of soils to manipulate the difference between apparent resistivity and pure resistivity of the soils under the assumption of the resistivity of pure water is the same [12].

Measurement of electrical resistance were done as follow; first, soils, pure water and leachate was prepared, and three sandy soils were measured its gravity, saturaton, water content and void ratio. Secondly, test specimen consisting of soil and pure water with leachate was filled into PVC chamber with a proper compaction (A-1 method) to simulate real ground conditions. Lastly, model dummy cone was installed to measure resistivity of soils. In this paper, to investigate the electrical resistivity of the experiments under the same conditions for test soils, four different unit weights with three different water contents were obtained from standard proctor compaction tests (Table 4). The optimum water content of the test soils should be determined to investigate sensitivity of resistivity before performing experiments, because soil resistivity was very different in resistivity variation with increasing water content before and after the optimum water content.

Table 4 show that three sandy soils used with four different dry unit density mixed with pure water and also three different percentage of leachate in volume. Most of water contents before experiments of the test soils were decreased after experiments. In this study, the water contents after experiments were used to analyze the sensitivity of resistivity variations with water contents.

The variation of electrical resistivity with changing water content, saturation degree, and unit weight were measured. In addition, to analyze the sensitivity of heavy metal concentration or pore fluid chemicals in soil phase to electrical resistivity, 5, 10 and 30% of leachate mixed with fresh water in volume were added to each soil. All the tests were performed at least duplicate under QA/QC management. If the test data for the duplicate samples are different more than 10%. Additional measurements were performed and the average values were taken from the test data.

4. Experimental results and discussion

4.1. *Effects of water content on resistivity measured*

The variations of electrical resistivity of Korean SAND, MASA and SAN-TO soils with changing water content are shown in Fig. 4, in which the resistivity values decreased as the water contents increased for SAND and MASA. However, this trend was not clearly observed for SAN-TO containing 8% of silty clay particles. SAND and MASA showed

Table 4
Determined dry unit weights and water contents for test soils

Soils	Dry unit weight (g/cm^3)	Water contents (%)		Leachate 5% (%)		Leachate 10% (%)		Leachate 30% (%)	
		Before	After	Before	After	Before	After	Before	After
SAND	1.55	19.0	16.5	19.0	21.3	19.0	16.2	19.0	18.1
		14.0	13.3	14.0	14.4	14.0	14.4	14.0	13.1
		10.0	9.4	10.0	9.7	10.0	10.2	10.0	9.4
	1.50	19.0	17.7	19.0	17.2	19.0	18.8	19.0	17.4
		14.0	13.2	14.0	13.6	14.0	13.6	14.0	13.1
		10.0	9.7	10.0	9.4	10.0	10.3	10.0	9.4
	1.45	19.0	17.9	19.0	17.9	19.0	19.1	19.0	19.3
		14.0	14.0	14.0	13.7	14.0	13.3	14.0	13.4
		10.0	9.6	10.0	9.5	10.0	10.0	10.0	9.6
	1.40	19.0	19.2	19.0	16.7	19.0	18.6	19.0	17.3
		14.0	13.8	14.0	13.1	14.0	13.8	14.0	13.7
		10.0	10.1	10.0	9.6	10.0	10.4	10.0	9.5
MASA	1.75	19.0	18.6	19.0	18.7	19.0	18.7	19.0	17.9
		14.0	14.0	14.0	13.9	14.0	14.0	14.0	15.0
		11.0	10.5	10.0	10.2	10.0	10.3	10.0	8.6
		7.0	7.4	–	–	–	–		–
	1.70	19.0	21.4	19.0	20.1	19.0	18.7	19.0	17.9
		14.0	14.7	14.0	14.3	14.0	14.0	14.0	13.5
		11.0	11.1	10.0	10.6	10.0	10.3	10.0	10.5
		7.0	7.0	–	–	–	–	–	–
	1.65	19.0	18.2	19.0	19.9	19.0	18.7	19.0	17.9
		14.0	13.2	14.0	13.9	14.0	13.6	14.0	14.0
		11.0	10.2	10.0	9.8	10.0	9.9	10.0	9.7
		7.0	7.2	–	–	–	–	–	–
	1.55	19.0	19.4	19.0	18.5	19.0	18.2	19.0	19.1
		14.0	12.5	14.0	13.9	14.0	13.7	14.0	13.9
		11.0	9.8	10.0	10.3	10.0	9.7	10.0	10.1
		7.0	6.2	–	–	–	–	–	–
SAN-TO	1.70	18.0	17.9	18.0	21.7	18.0	16.5	18.0	19.9
		14.0	14.6	14.0	15.9	14.0	13.7	14.0	14.0
		10.0	10.3	10.0	11.2	10.0	8.8	10.0	11.3
	1.60	18.0	17.7	18.0	20.4	18.0	16.7	18.0	20.1
		14.0	14.7	14.0	15.7	14.0	12.4	14.0	14.4
		10.0	10.3	10.0	11.2	10.0	8.0	10.0	10.7
	1.50	18.0	18.6	18.0	20.5	18.0	17.7	18.0	20.5
		14.0	16.2	14.0	15.7	14.0	12.4	14.0	15.9
		10.0	11.7	10.0	11.0	10.0	8.5	10.0	11.3
	1.40	18.0	18.2	18.0	19.9	18.0	17.4	18.0	20.9
		14.0	14.9	14.0	14.9	14.0	12.5	14.0	16.6
		10.0	11.3	10.0	11.0	10.0	10.0	10.0	12.0

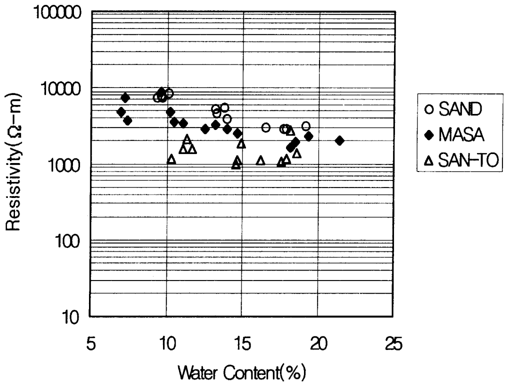


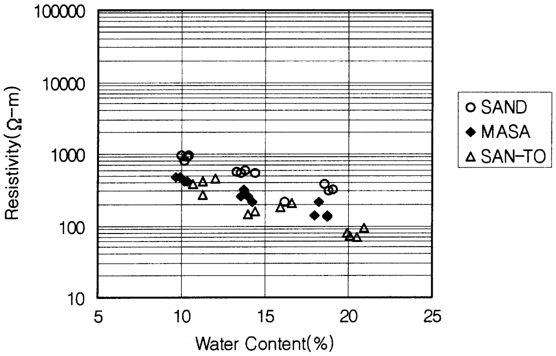
Fig. 4. Variation of resistivity with water content.

relatively higher resistivity values than SAN-TO. This can be explained as SAND and MASA contain more coarse-grained soil particles than SAN-TO (Table 1). The coarse-grained particles are primarily quartz and feldspars that have high electrical resistivity [17]. Also, the rates of decreasing resistivity with increasing water content in SAND and MASA were also higher than that of SAN-TO, which means that there was not much variation in resistivity values with increasing water content in SAN-TO.

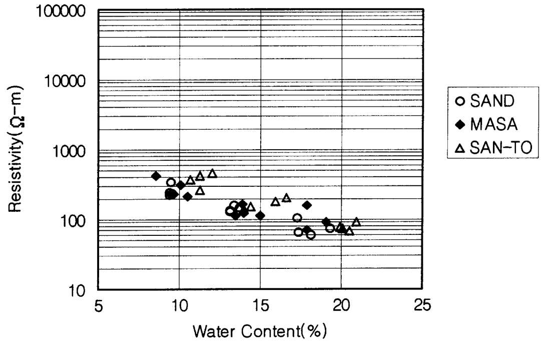
The water contents for the tests varied within 5 and 25%. As water contents increased, the electrical resistivities of SAND decreased from 8000 to 3000 Ω m, and the values for MASA also dropped from 6000 to 2000 Ω m. The results confirm that electrical conduction in sandy soils occurs primarily in liquid contained in the pores [19]. In contrast, the electrical resistivities of SAN-TO were not much affected by increasing water content, and stayed within 2000 and 1000 Ω m. In clay-bearing soils, electrical conduction occurs in the pores and on the surfaces of electrically charged clay particles, known as surface conductance [6,7]. For clays, surface conductance can be a significant factor affecting the bulk electrical resistivity of the soil [8,20]. For clay-bearing SAN-TO, electrical flow along the clay particle surfaces can be a dominant conduction mechanism. Thus, silty clay particles in SAN-TO were potentially responsible for making the soil relatively less sensitive to increasing water content in the resistivity measurements.

4.2. Effects of leachate on resistivity measured

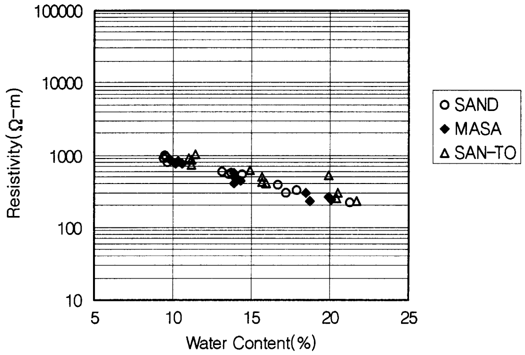
By adding 5, 10 and 30% of leachate mixed with fresh water in volume into three sampled soils, the variations of resistivity measured of three soils were observed with changing water content between 5 and 25% as shown in Fig. 5. There were significant drops in resistivity for three sampled soils by adding leachate compared with those values in Fig. 4. More electrical conduction occurred as a result of the movement of ions in the leachate. As the leachate contains various inorganic ions (Table 2(b)), the resistivity was affected to drop more significantly than that of water. For 15% water content, Fig. 6 shows that the resistivity of SAND dropped from 4000 to 500 Ω m by adding 5% of leachate, while SAN-TO showed



(a) 5% Leachate Proportion



(b) 10% Leachate Proportion



(c) 30% Leachate Proportion

Fig. 5. Variation of resistivity with leachate proportion.

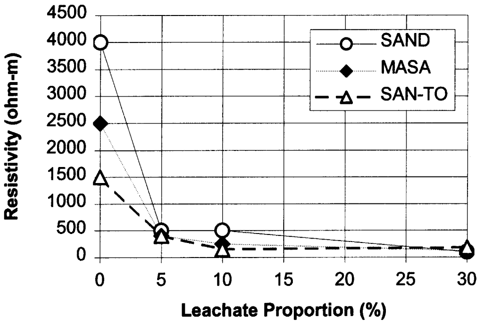


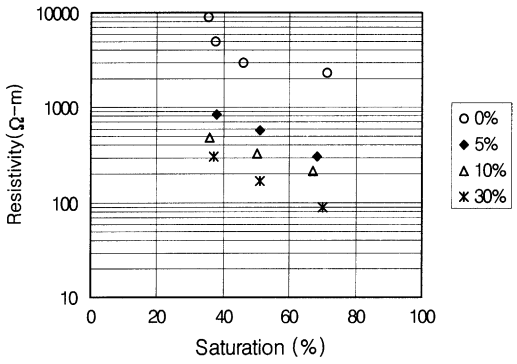
Fig. 6. Electrical resistivity variation with leachate proportion for 15% water content.

a relatively less sensitivity in dropping rate of resistivity measured than other soils because of 8% of silty clay particles. These fine-grained particles affected SAN-TO as more conducting material than other soils even before adding leachate. By having a higher percentage of fines, a lower electrical resistivity results. Soils with more fines often contain a higher percentage of conductive clay particles. Soils with higher fines content generally have higher specific surface, which improves surface conductance [21]. The important finding at this point is shown in Figs. 5 and 6, saying that the change in measured resistivity was extensively significant compared with resistivity variation in Fig. 4 by adding only 5% of leachate proportions. These facts say that electrical resistivity method can be a promising tool in the survey of existing contamination of the ground and well suited for monitoring of hazardous waste.

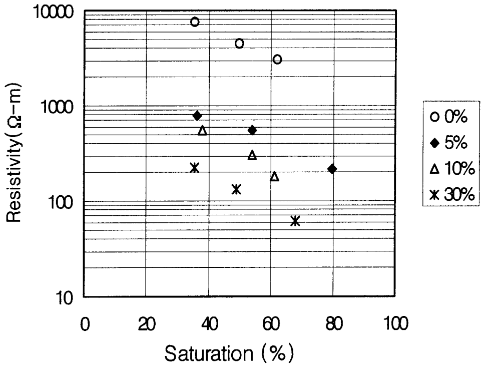
4.3. Effects of saturation degree and unit weight of soil on resistivity measured

To investigate the effects of saturation degree of the soil on resistivity change, the void ratio of the three sampled soils controlled by remolding soils after adding water, was used to measure the variation of resistivity in terms of controlling saturation degree to the extent 35–70%. Fig. 7 shows that the variation of resistivity measured of the three soils mixed with 0–30% leachate in volume with varying saturation degree. There were consistent trends in resistivity variations with increasing saturation degree and leachate concentration for three soils. Resistivities of the test soils decreased as the saturation ratio and the concentration of leachate solution increased for all cases. For each soil, electrical resistivity is inversely correlated to saturation degree.

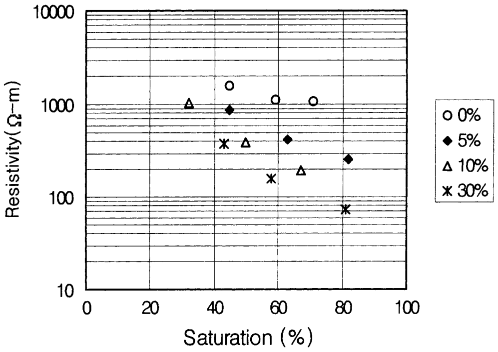
The resistivity of the SAND mixed with 0, 5 and 30% leachate in volume was observed by varying the unit weight from 1.4 to 1.55 kg/cm^3, and the observation results are shown in Fig. 8. The measured resistivity of the SAND was decreased with increasing water content and leachate proportions. There were, however, no remarkable differences in resistivity variation for all soils even though unit weight of the soils was much different at constant water content.



(a) Case of MASA Soil

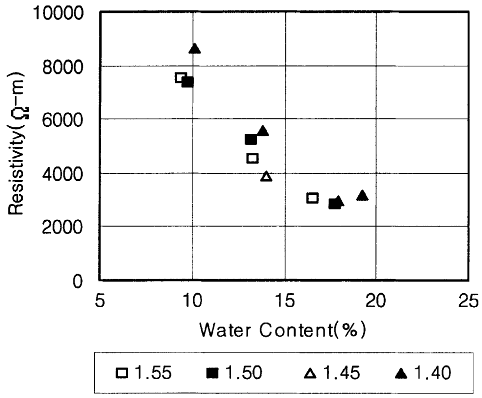


(b) Case of SAND Soil

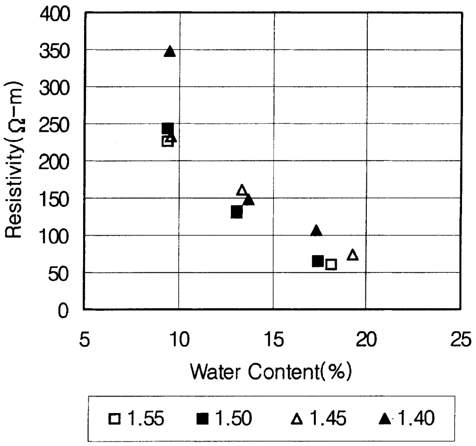


(c) Case of SAN-To Soil

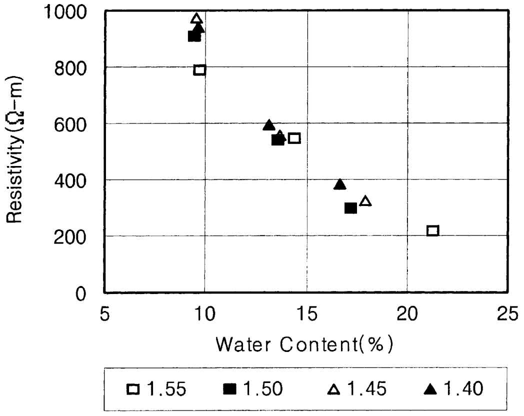
Fig. 7. Relationship between resistivity and saturation degree.



(a) 0% Leachate



(b) 5% Leachate



(c) 30% Leachate

Fig. 8. Relationship between resistivity measured and unit weight of SAND.

5. Conclusions

The following conclusions are drawn based on the parametric study.

1. Water content and pore fluid chemicals, leachate in this case, of the soils have much greater effects than unit weight and types of soils on variation of electrical resistivity measured.
2. There are significant differences between measured resistivity values of the soils before and after mixing leachate containing heavy metals. The decreasing rate of electrical resistivity measured with increasing contaminant proportion of leachate were significant, which indicates that electrical resistivity techniques can be successfully applied to detect contaminants at a problematic site, and to find the extent of the contaminant plume delineation.
3. There were similar trends in resistivity response with changing the unit weight, saturation degree, water content for sandy soil (SAND), weathered sandy soil (MASA), but silty clay soil (SAN-TO) showed a different trend in resistivity variations with changing unit weight, saturation degree and water content of soil. These can be explained due partially to difference in grain size distribution and larger percent of silty clay particles (8%). The clay contents in soil particles have significant effects on variation of electrical resistivity.
4. Further research is required on the resistivity variations of the clayey soils depending upon their mineralogy, and also on how the electrical resistivity of soil can respond with the various pore fluids in soil matrix.

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