Study on Measuring System of Subsurface Contamination using Complex Dielectric Method

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For evaluating subsurface contamination, sampling method (boring) is commonly used, but this method cannot monitor the change of in-situ contamination and concentration with respect to time. The purpose of this study is to develop a measuring system for subsurface contamination in which a so-called FDR-V system (Frequency Domain Reflectometry with Vector network analyzer) was employed to measure the salinity contaminant. This FDR-V method is a coaxial probe method, which allows the measurement of the complex dielectric constant from 1GHz to 18GHz. The experimental study indicates the possibility in measuring both the salinity concentration and volumetric moisture content.

Key words : Dielectric constant, Subsurface, Salinity concentration, Volumetric moisture content.

1 INTRODUCTION

Nowadays, the subsurface contaminant problem is a very important subject in all over the world. The study on this subject may often be faced with the difficulty in evaluating qualitatively the constituents of contaminated subsurface, like soil, pore air and pore water, because there is not yet a well-established and applicable sensor for such purpose.

For evaluating subsurface contamination at present time, the undisturbed sample is commonly taken out by sampling (boring) method, and then the contamination is extracted offsite. This method is not favorable to obtain an accurate data on the contamination rate and concentration, which are very important input data for modelling the evolution of solute concentration in the contaminated subsurface.

The recent application of measuring system of dielectric constant, Time domain reflectometry (TDR) developed by Topp et.al.(1980) for measuring θ (volumetric moisture content) makes possible accurate, continuous, real time and in-situ measurements. These methods are based on the dielectric method that the real part of the complex dielectric constant (ε') is not strongly frequency dependent on the frequency range of 1MHz to

1GHz, however, ε' appears to be highly sensitive to the ε and weakly sensitive to soil type and density. On the other hand, in the high frequency from 1GHz, the ε' depends on the frequency range and imaginary part of the complex dielectric constant (ε'') depends on the effect of dielectric loss. The dielectric loss is considered being equal to the rate of solute mixing in soils and water. In other word, it is possible to measure both ε and C by treating the complex dielectric constant.

Accordingly, as the purpose of this study is to develop the measuring system for subsurface contamination, in which the so-called FDR-V system (Frequency Domain Reflectometry with Vector network analyzer) was applied to measure the concentration of contaminant by using the two values of ε' and ε'' of complex dielectric constant.

2 METHODS

2.1 Complex Dielectric Constant

In this paper, the dielectric properties of soil and water is expressed by formula (1).

$$\varepsilon^* = \varepsilon' - j(\varepsilon'' + \sigma_{dc} / \omega\varepsilon_0) \tag{1}$$

where ε^* is the complex dielectric constant of the material, ε' is the real part of the complex dielectric constant that depends on the electric capacity, and ε'' is the imaginary parts of the complex dielectric constant

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that depends on the effect of dielectric loss. The electric capacity is the sensitivity influence of water volume, and the dielectric loss is considered being equal to the rate of solute mixing in soils and water. ε_{dc} is the static or dc conductivity, ε is the frequency of the wave, ε_0 is the permittivity of free space, and j is $-1^{1/2}$.

2.2 System Design of FDR-V

The FDR-V method used in this study is the coaxial probe method (one port reflective method and S parameter) which allows the measurement of the complex dielectric constant from 1GHz to 18GHz. For the purpose of measuring the concentration of a contaminant, this system separates two reflective electromagnetic waves, which consist of a real part and an imaginary parts of complex dielectric constant in the frequency domain.

2.3 Calculating Methods

The complex dielectric constant obtained from this system is calculated by formula (2).

$$\varepsilon^* = \frac{\varepsilon^*_a (\rho_{mm} - \rho_{mo})(\rho_{ms} - \rho_{ma}) + (\rho_{mm} - \rho_{ma})(\rho_{mo} - \rho_{ms})}{(\rho_{mm} - \rho_{ms})(\rho_{mo} - \rho_{ma})}$$

(2)

where ε^*_a is the value of known complex dielectric constant of standard material. This system uses pure water or Acetone as a standard material. ε is the coefficient of reflections calculated by relative complex amplitude (variations in amplitude and phase angle) between entry microwave and reflection microwave. ρ_{mm}, ρ_{mo}, ρ_{ms}, ρ_{ma} are the coefficients of reflection calculated from the measured material, open ($\varepsilon=1$), short ($\varepsilon=\infty$), standard materials (Pure water or Acetone), respectively.

3   DIELECTRIC PROPERTIES OF SALINE WATER

3.1 Temperature dependence for complex dielectric constant for water

The relationship between complex dielectric constant and frequency from 1GHz to 18GHz measured by the FDR-V system on pure water at 20℃ is shown Fig.2. The relationship indicates that the real part of the complex dielectric constant decrease and the imaginary part of the constant increase with the increase in frequency. This study focused on the four values ε'_1, ε'_{18}, ε''_1 and ε''_{18} (1GHz and 18GHz of the real and

(a) General view of system

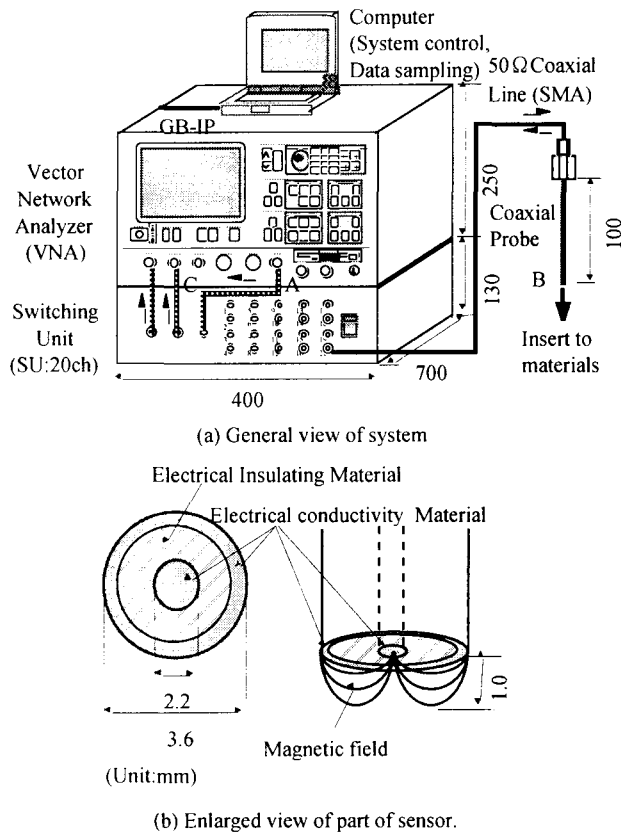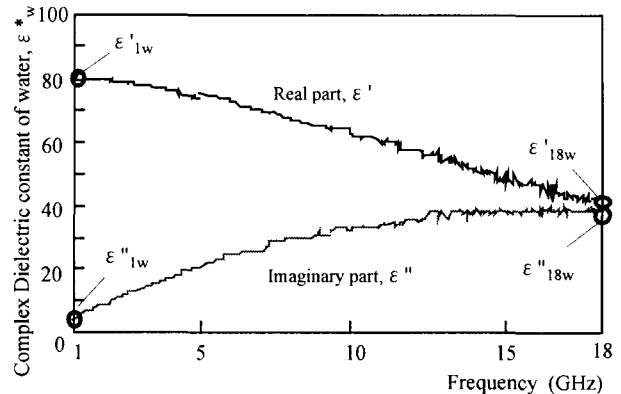(b) Enlarged view of part of sensor.

Fig.1 FDR-V system.

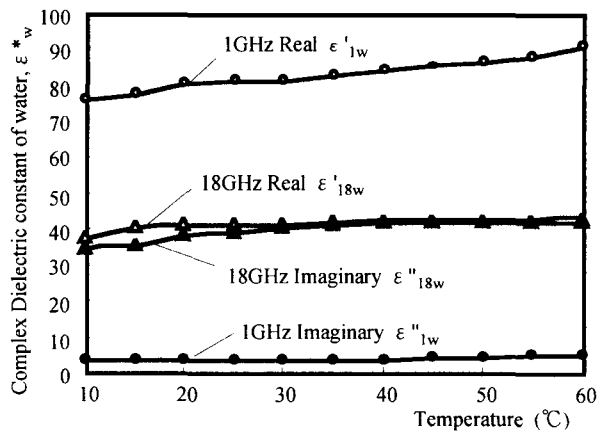**Fig.2** Complex dielectric constant of pure water versus frequency for 20℃

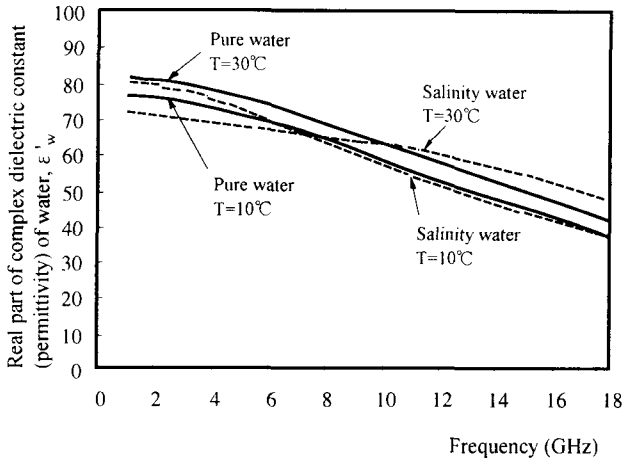**Fig.3** Relationships between complex dielectric constant and temperature of pure water.

Fig.4 Real part of complex dielectric constant versus frequency for 10°C and 30°C of pure water and saline water. Salinity of water is 2000ppm.
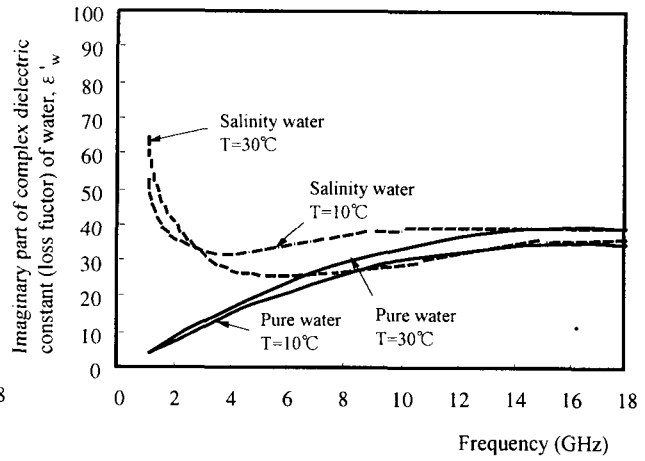

Fig.5 Imaginary part of complex dielectric constant versus frequency for 10°C and 30°C of pure water and saline water. Salinity is 2000ppm.
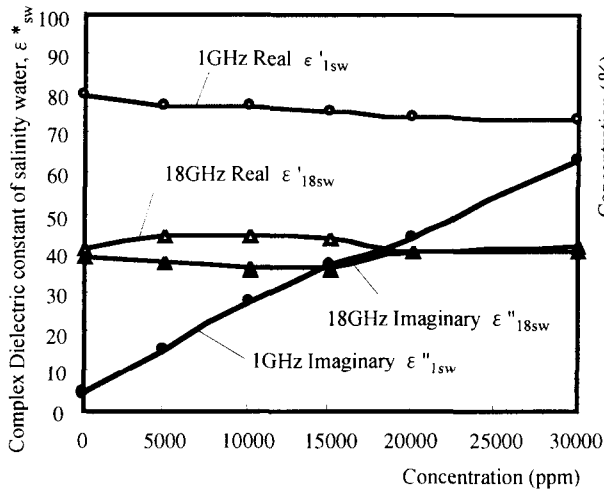

Fig.6 Relationships between complex dielectric constant and concentration of saline water.
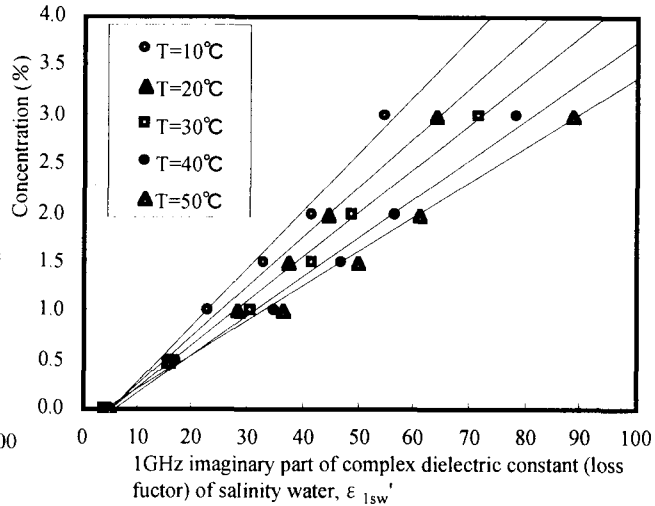

Fig.7 1GHz imaginary part of complex dielectric constant versus concentration of saline water for T=10°C~50°C.

imaginary parts of the complex dielectric constant) obtained from the measurement. Fig.3 shows the temperature dependence of the complex dielectric constant of pure water for ε'_1, ε'_{18}, ε''_1 and ε''_{18} which indicates that the effect of temperature is very significant at highly dielectric constant.

3.2 Salinity dependence for complex dielectric constant for water

To evaluate the effect of salinity on water, the dielectric properties of pure water and saline water are compared, as shown in Fig.4 and 5. Fig.4 illustrates the relationship of the real part of the complex dielectric constant with frequency at 10°C and 30°C. The results of the spectrum do not specify the difference for pure water and saline water. On the other hand, the comparison for the imaginary part indicates a significant difference

between pure water and saline water at the frequency range between 1GHz and 5GHz. To clarify this result, the relationship between complex dielectric constant and concentration of saline water is plotted in Fig.6. The plot indicates that the imaginary part at 1GHz increases with concentration. Therefore, it is possible to determine the concentration by treating the imaginary part at 1GHz.

3.3 Estimating concentration

To determine the concentration saline water, the relationship between 1GHz imaginary part of complex dielectric constant and concentration at temperature from 10°C to 50°C was established (Fig.7). The relationship indicates the increasing effect of concentration on 1GHz imaginary part of the complex dielectric constant at the given temperature range. Then, by using multiplex linear recurrent analysis, the following estimation of

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concentration is obtained :

$$C = 6.19 \times 10^{-2} \varepsilon'_{1sw} + 2.97 \times 10^{-3} T$$
$$- 5.40 \times 10^{-4} \varepsilon'_{1sw} T - 3.48 \times 10^{-1} \quad (R^2=0.99) \quad (3)$$

where T is temperature (℃), ε''_{1sw} is 1GHz imaginary part of complex dielectric constant. The experimental results shows a good agreement with the calculated results, as indicated in Fig.8.
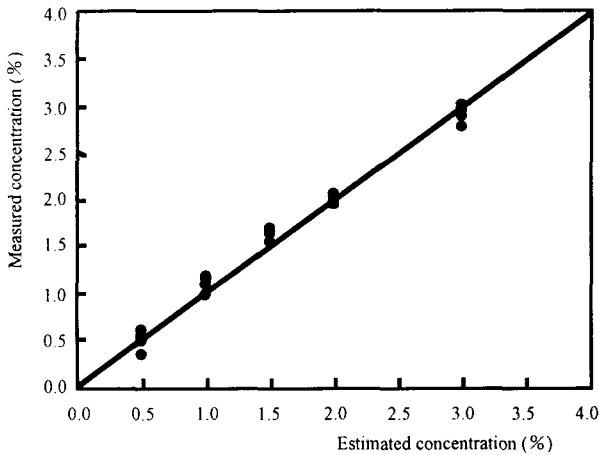

Fig.8 Fitting results.

4 DIELECTRIC PROPERTIES OF SALINE SOIL

4.1 Salinity dependence on the complex dielectric constant for water

In the absence of liquid water, the real part of the microwave complex dielectric constant of soil, ε'_{soil}, varies over the range between two and four, and the imaginary part, ε''_{soil}, is typically <0.05 [Topp et.al.(1980)]. On the other hand, in the case of wet soil, ε'_{soil}, varies over the volume of moisture, and ε''_{soil}, varies over the degree of dielectric loss. In addition, the complex dielectric constant is dependent on temperature, but in the case that dielectric constant is low value, it can be considered that the temperature effect is less significant. So, in this study, the measurement was carried out under the constant temperature 20℃. The sample used in this measurement is fine sand, having a specific gravity of 2.65 and effective particle size $D_{10}=0.08mm$, $D_{60}=0.8mm$, the condition is dry density $p_d=1.50g/cm^3$, porosity n=0.43.

Fig.9 shows the complex dielectric constant versus frequency of wet soil under volumetric moisture content θ = 0.17, for salinity concentration of 0 ppm and 20,000ppm. It is considered that the real part does not show difference, but the imaginary part of the C=20,000ppm at the range of 1GHz to 5GHz is becomes higher than that of the C=0ppm.

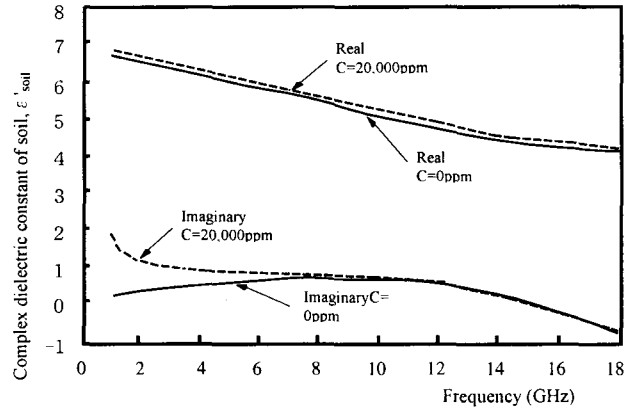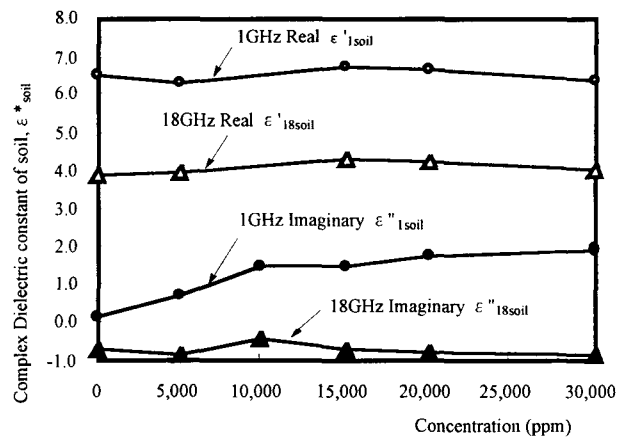Fig.9 Complex dielectric constant versus frequency of soil for salinity (fine sand: θ =0.17, n=0.43).

Fig.10 Relationships between complex dielectric constant and concentration of salinity soil.(fine sand : θ =0.17, n=0.43)

Similar to saline water measurement, this study focused on four values of this measurement data, ε'_{1soil}, ε'_{18soil}, ε''_{1soil}, ε''_{18soil} (1GHz and 18GHz real and imaginary part). The relationship between complex dielectric constant and concentration is shown in Fig.10. The three value of ε'_{1soil}, ε'_{18soil}, ε''_{18soil} are constant, but the 1GHz imaginary part have essentially the dependence upon concentration.

4.2 Estimating concentration and volumetric moisture content

To estimate concentration and volumetric moisture content from the output data of the FDR-V system, the relationships between 1GHz real part ε'_{1soil} and imaginary part ε''_{1soil} of complex dielectric constant versus volumetric moisture content for difference salinity concentration are plotted, and shown in Fig.11 and Fig.12, respectively. It is clear from this figure that the ε'_{1soil} only depends on volumetric moisture content and ε''_{1soil} depends on both volumetric moisture content and
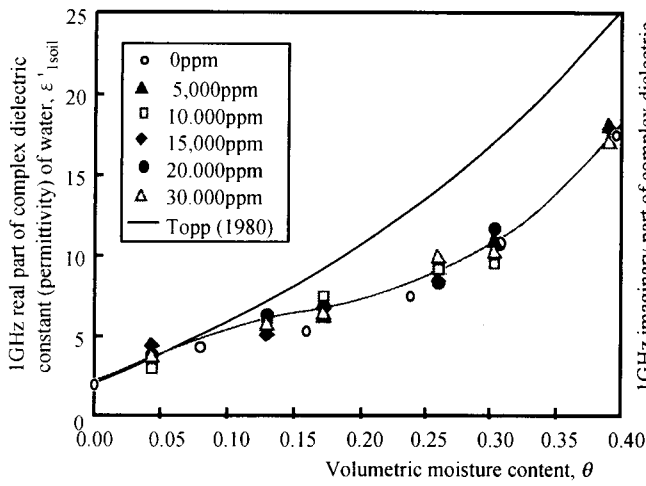
Fig.11 Real part of complex dielectric constant versus volumetric moisture content for different salinity of soil.
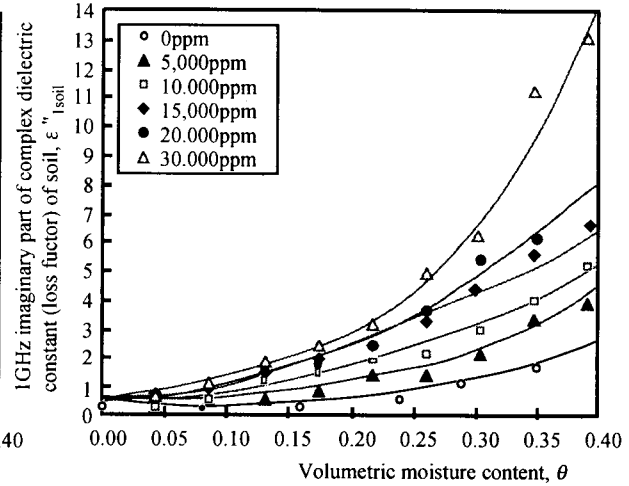(fine sand : porosity n=0.43)

Fig.12 Imaginary part of complex dielectric constant versus volumetric moisture content for different salinity of soil.
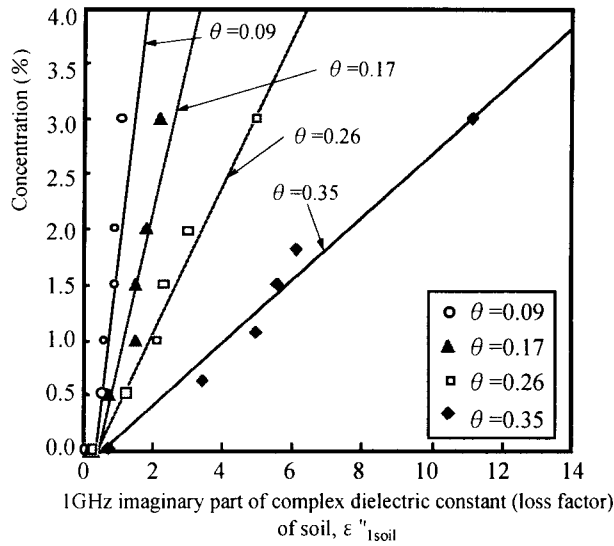(fine sand : porosity n=0.43)

Fig.13 1GHz imaginary part of complex dielectric constant versus concentration of salinity soil for different volumetric moisture content θ.
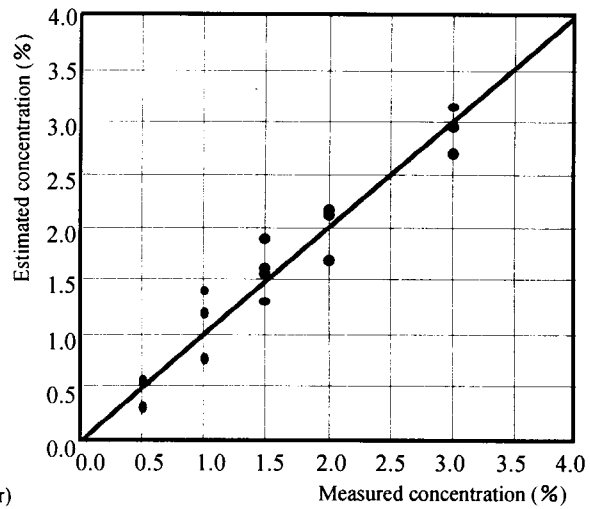

Fig.14 Fitting results.

salinity concentration.

The volumetric moisture content is estimated by the following equation of third order polynomial.

$$\theta = -4.93 \times 10^{-5} \varepsilon'_{1soil}{}^{3} - 2.09 \times 10^{-4} \varepsilon'_{1soil}{}^{2} + 4.85 \times 10^{-2} \varepsilon'_{1soil} - 1.29 \times 10^{-1} \quad (R^2 = 0.98)$$

(4)

Fig.13 shows the relationship between ε''_{1soil} and salinity concentration at four value of θ. The data enables to make linear approximations for each θ. Then, the multiplex linear recurrent analysis was run to this measured data, and the equation to estimate salinity concentration C(%) using two values of ε''_{1soil} and θ is obtained as follows.

$$C = 6.42\theta - 0.16\varepsilon''_{1soil} + 8.26\varepsilon''_{1soil} \cdot \exp(-8.67\theta) - 2.03$$
$$(R^2 = 0.90) \qquad (5)$$

This fitting result is shown in Fig.14, and indicates data scattering at the range of 1 % , but the trend of concentration can be estimated. Future research is needed to improve the accuracy of the FDR-V method.

5 CONCLUSIONS

In this paper, to develop the measuring system for subsurface contamination, what so-called FDR-V system (Frequency Domain Reflectometry with Vector network analyzer) was applied to measure the concentration of contaminant. The following conclusions may be drawn

from this study : (1) It is showed that the concentration of saline water can be estimated from 1GHz imaginary part, ε''_{lw} of complex dielectric constant. (2) In the case of saline soil, both volumetric moisture content and salinity concentration can be estimated from 1GHz real and imaginary part, ε'_{lsoil}, ε''_{lsoil} of complex dielectric constant at the one time measurement by using FDR-V system. The advantage this method is owing to its simplicity and the small size of the sensor.

Further study will be required to increase the accuracy of this FDR-V system, and to apply the system for other materials.

REFERENCES

Topp,G.C., J.L.Davis, A.P.Annan (1980) ; Electromagnetic Determination of Soil Water Content : Measurements in Coaxial Transmission Lines, *Water Resour. Res.*, Vol.16, No.3, pp.574-582.

Topp,G.C. M.Yanuka, W.D.Zebchuk, S. Zegelin (1988) : Determination of Electrical Conductivity Soil and Water Experiments in Coaxial Lines, *Water Resour. Res.*, Vol.24, No.7, pp.945-952.

Fawwz T. U., K. M. Richard and K. F. Adrian (1986) : MICROWAVE REMOTE SENSING, Active and Passive, Volume III, From Theory to Applications, *Artech House, INC.*, pp.2017-2103.

Udo K. (1989) : Complex Permittivity of Water as a Function of Frequency and Temperature, *Journal of Chemical and Engineering Data*, Vol.34, No.4, pp.371-374, 1989.