Nishigaki, M., Komatsu, M., Kim, M.-I., An experimental approach for estimating the porosity and effective porosity of porous media by permittivity methods.
International Symposium on the Fusion Technology of Geosystem Engineering, Rock Engineering and Geophysical Exploration
Seoul, Korea, Nov. 18-19, 2003

An experimental approach for estimating the porosity and effective porosity of porous media by permittivity methods

M. Nishigaki[1], M. Komatsu[1], M.-I. Kim[2]
[1]Faculty of Environmental Science and Technology, Okayama University, Okayama, Japan, [2]Graduate School of Natural Science of Technology, Okayama University, Okayama, Japan

Abstract: In the sub-surface environments, detection of the movement of contaminant substances and recharge of groundwater by rainfall are very important factors which contain porosity and effective porosity of porous media. In this paper, the applicability of permittivity methods and proposed dielectric mixing models (DDMs) are discussed. This study showed that the ratio of effective porosity to porosity of Toyoura and River sands were 0.856 and 0.843. From the relationships between the relative porosity and effective porosity, all measured values can be confirmed to outside the range to about 0.800 for Toyoura and River sands under all experiments by FDR and FDR-V systems. In the study, this permittivity equipment can be considered to be good enough to measure determining the physical parameters of saturated soils. Consequently, this permittivity method can be contributed to estimate a porosity and effective porosity of saturated porous media because it is easy and instantaneous than previous in-situ methods.

1. Introduction

In the porous media, determination of moving passages of a contaminant material from the surface or movement of groundwater in the sub-surface is one of the very important factors to understand in a ground structure. It is mainly achieved through a pore which is a spatial conception of the sub-surface. The movements of a variety of solution materials can be known according to the connectivity of pore. Therefore, these are displays as the concepts of porosity and effective porosity: the former is the ratio of pore space to total volume, and the latter is the degree of interconnection of pores in the porous media. Effective porosity is generally plays an important role of the passage of them.

To estimate these parameters of porous media, numerous investigators have been conducted in-situ experiments as a variety of applied tracer and well tests using excavated boring holes in the field (Tonder et al., 2002; Singh, 2002). Furthermore, several researchers were carried out laboratory column tests for measuring factors to use a fine grain material such as clay, silt and bentonite (Zheng et al., 2002; Kim et al., 1997). Li et al. (1996) reported the hydrologic properties that govern fluid flow through the sub-surface are porosity, permeability, relative permeability, pore and grain particle size distributions. Therefore, the variation factors of movement and attenuation of the tracer material are easily changed of hydrologic properties in sub-surface porous media due to chemical and biochemical processes. These processes can be also applied to be contaminant solutions. Since these tracer materials are environmentally friendly, they are very useful in groundwater flow and contaminant studies. The aims of these applied experiments can be explained to estimate a velocity of groundwater, coefficient of advection or dispersion, porosity or effective porosity of porous media due to movement velocity of tracer materials in the field or laboratory. However, previous researches are required a lot of experimental periods and costs for estimating these parameters through an applied tracer experiment. Despite of these experiments, quantitative result shows a difficulty to estimate a corrective parameter. Therefore, economical and utilizable measuring method is required to know the parameters in the field and laboratory.

To understand a structure of porous media, lots of researchers have been studied to widely use an applied Time domain reflectometry (TDR) method which is carried out to soils and rocks from relate to the response of relative dielectric constant. It is also applied to estimate volumetric water content, soil density, concentration of salinity and other parameters in the sub-surface (Jones and Or, 2001; Chenaf et al., 2001; Drnevich et al., 2001; Rassam and Williams, 1997; Topp et al., 1980). From the results of them, permittivity method is able to know to offer very quantitative profiles of porous media, as well as short measuring period. Therefore, if applied permittivity method is used, physical parameters of porous media can be easily estimated.

In this work, we proposed a measuring method using the permittivity systems such as Frequency domain reflectometry (FDR) and Frequency domain reflectometry with vector network analyzer (FDR-V) systems to estimate porosity and effective porosity of porous media. In order to discuss with an in-situ experiment using permittivity systems, we estimate a soil column injection experiment using the fully saturated Toyoura and River sands by FDR and FDR-V systems in the laboratory. It is mainly consisted of two kinds of column experiments: the former is an injection test, and the latter is a replacement test by using two systems. From the all experimental results, we are carried out a comparison of the calculated effective porosity from both the permittivity methods and the soil column replacement test, and an examination of an applicable possibility to the permittivity method using the FDR and FDR-V systems. Furthermore, we are tried to compare with the relationship between porosity and effective porosity through the whole experiments. Specially, in the case of an effective porosity, we discuss to verify an accuracy of it from the relationship between an injection, replacement and tracer tests.

2. Experimental methodology

Dielectric permittivity systems

In this study to estimate porosity and effective porosity, we used two kinds of permittivity systems: one is a Frequency Domain Reflectometry (FDR) system and the other is a Frequency Domain Reflectometry with Vector Network Analyzer (FDR-V) system. These systems were used to measure the relative dielectric constant for the fully saturated sands in a variety of experimental situations. To understand the degree of saturation for manufactured soil columns, we used the back pressure method (Shackelford and Redmond, 1995; Shackelford, 1994; Tada, 1994; Campbell, 1973). The FDR system using a response of impedance of the frequency range was one of the permittivity methods to measure soil physical parameters in the special depths for sub-surface. It was consisted to five apparatuses, that is, tracking generator, CM directive coupler, spectrum analyzer and data logger. A FDR rod probe was installed for a measuring point location, and it was then measured a relative dielectric constant of the soil material, instantaneously. A measurable range of FDR rod probe in porous media was at least 4 cm in diameter and 2 cm end of its tip. The frequency range of FDR system was used a 100 MHz to 1.7 GHz.

The FDR-V system consisted of mainly three sets of apparatuses such as vector network analyzer, switch unit and data logger. A vector network analyzer operated to control all system functions, a switch unit was connected a 50-ohm coaxial transmit cable with connect a measuring coaxial probe on its tip, and a data logger was able to control the FDR-V system and collected experimental data with consistent travel time in whole experiment. FDR-V system utilized microwave frequency range from 100 MHz to 3 GHz. A measuring range of its probe had about 0.2 cm in diameter at the end of its tip in porous media, but the range of a measuring frequency was only used a 1 GHz. Measured frequency for both systems were used only 1 GHz of measured frequency, and we were able to use a measured relative dielectric constant to estimate the porosity and effective porosity by using the dielectric mixing models.

Dielectric mixing models

The composed materials of porous media were mainly consisted of three phases as soil grain particle, air and water. It is also represented to the amount of air and water which are existed with inner of fully saturated or unsaturated conditions, as well as known to mostly exist of fully saturated condition included to groundwater. Natural soils keep a moisture water content in between particle grains as well as bound water around soil particle grain materials. These absorbed water might be consequently represented a degree of saturated condition of artificial or natural soil and determined a response of relative dielectric constant under permittivity methods. Ethanol liquid as used tracer injecting material can play a role of displace to contained water and bound water in the soils. It will be filled with a soil particle structure instantaneously, but keeps an essential soil structure when ethanol is infiltrating. Therefore, water fully saturated soil is displaced to be become an ethanol saturated condition, and slowly changed a relative dielectric constant with an ethanol infiltration. Here, the variations of relative dielectric constant by ethanol liquid can be perceived through the ethanol injection with travel time.

Therefore, each relative dielectric constant for porous media composed was already reported by Curtis and Defandorf (1929). For example, dielectric constant of water, air and soil are 80, 1 and 2-3, respectively, at 20 °C. According to variation of measured dielectric constant, dielectric mixing models (DDM) were proposed to estimate a porosity and effective porosity of fully saturated porous media. It can be applied to measure porosity when porous media is completely saturated condition with water into soil particles. It can be written by the following relationship as:

$$\varepsilon_{init} = \varepsilon_s (1 - n) + \varepsilon_w \cdot n \quad (1)$$

As injecting a tracer or injection material as ethanol liquid into fully saturated porous media, the existed water into the soil particles will be displaced by ethanol liquid. These procedures were achieved to be changed ethanol liquid to exist absorbed water in the fully saturated soil particles which is open pore conditions, however, bound water does not move or displace because soil particles are closely emitted which shows a death-end pore conditions. Therefore, movement of ethanol liquid into fully water saturated material could be occurred to an ethanol displace action within the connected pores between soil particles. Consequently, injection and displace action of ethanol liquid is only generated to connected pores which is described to the concept of effective porosity. To consider displace effect, its action is described to the following relationship as:

$$\varepsilon_{final} = \varepsilon_s(1-n) + \varepsilon_w(n-n_e) + \varepsilon_{eth} \cdot n_e \tag{2}$$

The relationship between equations (1) and (2) for effective porosity is written by:

$$n = \frac{\varepsilon_s - \varepsilon_{init}}{\varepsilon_s - \varepsilon_w} \tag{3}$$

$$n_e = \frac{\varepsilon_{init} - \varepsilon_{final}}{\varepsilon_w - \varepsilon_{eth}} \tag{4}$$

where, n and n_e are the porosity and effective porosity, respectively. ε_{init} and ε_{final} are an initial measured relative dielectric constant of real part at 1 GHz, and ε_s, ε_w and ε_{eth} are the relative dielectric constant of soil, water and ethanol, respectively.

Experimental methods

In order to estimate porosity and effective porosity, two kinds of sand materials were prepared such as Toyoura and River sands. All sands were carried out of the sieve test to analyze of soil particle distributions. Table 1 shows the results of grain size distribution for each of the sands from the sieve test. According to the particle size distribution curves, Toyoura sand showed a very sharp gradient because they are coarse size material of more than 90 %. On the other hand, River sand represented an irregular feature because it contains variable grain sizes, from very coarse to fine. Therefore, Toyoura sand can be considered to be the uniform sand, i.e., the most of the grains are the same grain size and the uniformity coefficient (ratio of the 10 % to 60 % of grading curve) was 1.607 from derived particle distribution curve. The uniformity coefficient of River sand also calculated 6.928. However, the uniformity coefficient of the uniform soil was theoretically assumed to be 1.0 (Head, 1980). Here, the River sand showed different grading curve, from coarse gravel to fine silt. It is described as a gap-graded material and, in natural soils, the deficiency usually occurs in the coarse sand to fine gravel range. The content of fine grain material as like silt and clay for River sand presented larger than Toyoura sand, which play an important part of interrupt a movement of some liquid material.

Table 1. Physical properties of sands.

Sand	Distributions of particle size (%)				Specific gravity (g cm $^{-3}$)
	Gravel	Sand	Silt	Clay	
Toyoura	0.00	99.90	0.10	0.00	2.65
River	15.50	81.70	2.80	1.00	2.69

Distributed particle size: 60~2 mm for gravel, 2~0.06 mm for sand, 0.06~0.002 mm for silt and less than 0.002 for clay

In this study, we were prepared to three kinds of soil column experiments - soil column injection test and soil column replacement test. Here, we used ethanol 95 % liquid for injection test and replacement test, individually. All tests were used a fully saturated Toyoura and River sands which are made to keep an estimated porosities - 0.35 0.40 and 0.45, respectively. In the soil column injection test, FDR and FDR-V systems were used to measure a relative dielectric constant of initial and final values through the whole injection test. And soil column replacement test was simultaneously conducted with the soil column injection test because of need to only simple parameters, that is, total effluent quantity, total injected ethanol quantity and concentration of effluent quantity.

3. Results

Calibration curves of sands

Calibration curve of soil is very important to understand the relationship between volumetric water content and relative dielectric constant. It is easy to estimate a volumetric water content, soil density and degree of saturation for comparing with measured relative dielectric constant of a variety of porous media in the laboratory or field. The relative dielectric constant of water was generally announced much larger than other soil constitute. Therefore, the determining volumetric water content by measuring relative dielectric constant of moist soil is quite reasonable. For the homogeneous soils, volumetric water content θ is then calculated using the empirical calibration curve determined by Topp et al., (1980):

$$\theta = 4.3\times10^{-6}k^3 - 5.5\times10^{-4}k^2 + 2.92\times10^{-2}k - 5.3\times10^{-2} \quad (5)$$

where θ and k are the volumetric water content and relative dielectric constant.

Relative dielectric constant measured by permittivity methods can be sufficiently measured in a variety of the relative physical parameters from soils in laboratory and field experiments. These parameters were included a volumetric water content, degree of saturation, bulk density, porosity and effective porosity, which are able to calculated by the permittivity methods. To confirm these parameters all calibration curves are needed to the acquirement of sand materials. It is required to several sand samples containing different volumetric water content and fully saturated sand sample which has the same estimated porosity. Fig. 1 shows the measured calibration curves for Toyoura and River sands for all porosities, 0.40 and 0.45, and additionally if shows a comparison with the empirical calibration curve of Topp.

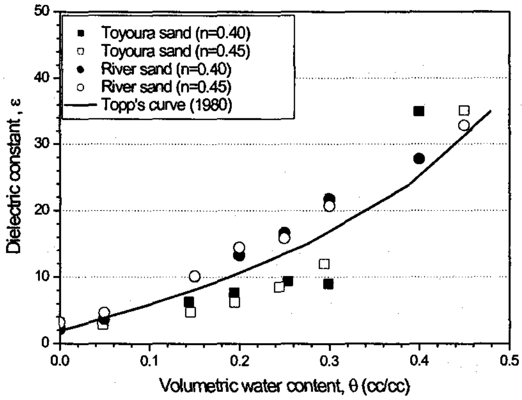


Fig. 1. Calibration curves for each of sands.

In Fig. 1, calibration curve of Toyoura sand is displayed a little lower than Topp's empirical curve in the volumetric water content 0.0 to 0.3 ranges for measured the relative dielectric constant. However, over 0.4 of the volumetric water content was represented higher than the Topp's empirical curve. In the River sands, calibration curves showed nearly same to the relative features. All other curves for sands – Toyoura and River - are assumed to nearly similar forms to compare with Topp's empirical curve. These differences form for each plotted sands with Topp's curve can be explained to the distributions of soil particle size. Topp's study was only used a soil with clay and slit loam, that is, very fine soil materials. Here, the porosity of all soils at the fully saturated conditions includes general means an equal to the volumetric water content (Wilson et al., 1995). Therefore, a corrective calibration curve can be used to calculate a porosity, degree of saturation and other parameters from an acquired relative dielectric constant at 1 GHz by the permittivity methods, as well as the natural volumetric water content of the in-situ porous media can be confirmed to compare with each the calibration curve for the soils.

Temperature dependencies of dielectric constants

The effect of temperature dependency might account some differences between the present calibration and that of Topp et al. (1980), as the experiments were conducted at a temperature lower than normal in-door temperature. The relative dielectric constant is known to very sensitive to the effect of temperature at the circumference of laboratory or field. Therefore, we discussed to a temperature dependency for the relative dielectric constant under an estimated

Table 2. Relative dielectric constant of soil constituents and major textures of soils (from Curtis and Defandorf, 1929).

Material	Relative dielectric constant
Air	1 (0.85 ~ 1.21 at 20 ∘C)*
Water	80 at 20∘C (79.50 ~ 80.24)*
Ice	3 at -5 ∘C
Basalt	12
Granite	7 ~ 9
Sandstone	9 ~ 11
Dry loam	3.5
Dry sand	2.5 (2.5 ~ 3.5 at 20∘C)*
Ethanol (95%)*	15.21 at 20 ∘C*
Ethanol mixing liquid*	39.82 at 20 ∘C*
Acetone*	21.20*

* measured the relative dielectric constant in this study

constant temperature by using a temperature container. Table 2 lists the variation of relative dielectric constant for several materials at 20 °C, which is compared to the empirical data (Curtis and Defandorf, 1929) with the measured real profiles by permittivity method.

According to Jacobsen et al (1993), under climatic temperature conditions, in-situ soil temperature will normally be lower than in-door temperature. In water the relative dielectric constant would change from 75 to 84 if the temperature were changed from 10 to 36 °C. The relative dielectric constant of water shows a similar value, which indicated the range of about 72 to 85 at same temperature ranges in this study. Therefore, the measured results show the similarity of the variation of the temperature dependency for the measured relative dielectric constant of water. Furthermore, 95 % ethanol and Toyoura sand are showed the relationship between relative dielectric constant and temperature.

Relationships between dielectric constant, porosity, and effective porosity

For measuring porosity from relation of relative dielectric constant by using FDR and FDR-V system, we used only the initial value which indicated a relative dielectric constant of fully saturated sand. It was also changed to different estimated porosity. DDMs were used from the relation of relative dielectric constant of soil, water and measured initial value to establish porosity of saturated soils. Therefore, we tried to compare with estimated porosities - 0.35, 0.40 and 0.45 - and measured porosity by using the DDMs for two systems.

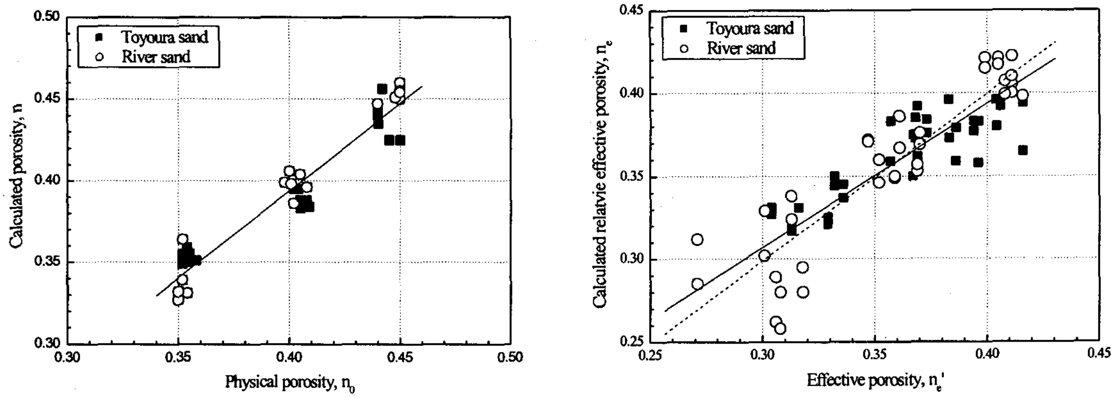
In Fig. 2, the plotted measured porosities were shown within the range of nearly 94 % with the estimated porosities for Toyoura and River sands. And the measured porosities by FDR system were also indicated to within the range of 95 % for two fully saturated sands comparing with a 1:1 fixed scale. Comparing with these porosities by the soil column injection, they presented to within the range of almost 95 % for Toyoura and River sand under FDR and FDR-V systems. From these results of porosity profiles, two permittivity systems should be measured more corrective porosity value of saturated sands. Relation of dielectric constant and porosity shows on Fig. 3. According as measured values of dielectric constant increases, tendency that porosity increases together is seen. These causes become involved with volume of pore between soil particles. That is, because volume of water included in pore according as porosity is increased, it is judged that measurement of measured dielectric constant appears high value of saturated soils.

Comparison of effective porosity between soil column tests

The values of effective porosity are generally smaller about 80 to 90 % for porosity of the natural soils. Therefore, the spatial conduit supported to porosity of the soils is easily changed with the soil composition and structure, as well as distributions of soil particle size.

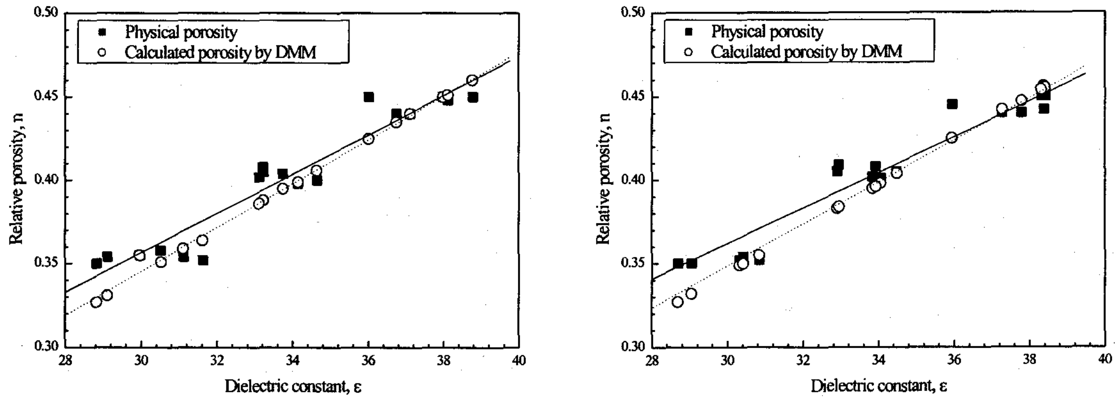
Fig. 4 displays relation of effective porosity and porosity. In the case of Toyoura sand, measured effective porosity between injection and replacement tests were shown the similar distributions under FDR and FDR-V systems. It was distributed within the range of 85 % comparing to an estimated porosities. And measured effective porosity of River sand measured by FDR-V system was presented the similar tendency with FDR system at the range of 0.40

to 0.45 for the estimated porosity. On the range of 0.35 to 0.40 for the estimated porosity, however, the result of FDR system was shown a little lower than FDR-V system. This reason was judged to the content of fine materials such as clay and silt, which has an influence of the relative dielectric constant of sand materials.



(a) Physical porosity to calculated porosity (b) Effective porosity to calculated relative effective porosity

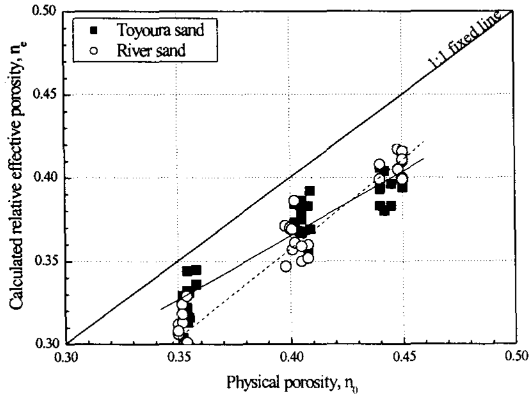
Fig. 2. Distributions of measured values for porosity and effective porosity of saturated sands under injection and replacement tests by using FDR and FDR-V systems.



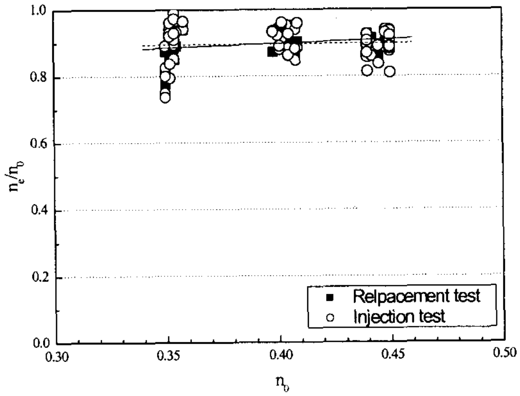
(a) FDR-V system (b) FDR system

Fig. 3. Relationship between dielectric constant and porosity of saturated sands by FDR and FDR-V systems.

For the purpose to estimate an effective porosity in the laboratory test, we were carried out of two kinds of experimental methods. It was provided to the profile of effective porosity for fully saturated sands. In the case of Toyoura sand using two systems, the relationship between effective porosities was presented within the range of almost +/- 10 % to a 1:1 fixed scale. However, derivation of River sand was shown within the range of nearly +/- 13 % comparing with the 1:1 fixed scale. As compare the injection test with the replacement and tracer tests, the results of injection test were plotted a little small around 0.35-effective porosity for fully saturated Toyoura sand than other tests under FDR and FDR-V systems. However, the effective porosity of River sand by derived the injection test were distributed to comparative similar range of 0.25 to 0.40 for other values. To consider a measuring range of the measuring probe for FDR-V and FDR systems, a FDR measuring probe can be measured until a 15 cm depth than FDR-V measuring probe, which is only measured a pin point like as the end of tip for it.



(a) Physical porosity to effective porosity



(b) physical porosity to ratio of effective porosity and physical porosity

Fig. 4. Relationships between the relative effective porosity and physical porosity of saturated sands.

4. Conclusions

In this study we were carried out to estimate porosity and effective porosity of the fully saturated Toyoura and River sands under two kinds of soil column tests such as injection and replacement tests, in the laboratory, using the frequency domain reflectometry with vector network analyzer (FDR-V) and frequency domain reflectometry (FDR) systems. Two different fully saturated sands of Toyoura and River were used and the all experiments were carried out under constant temperature in the laboratory. The measuring probes that were used of fixed size lengths 5 cm for FDR-V and 15 cm for FDR systems. Several conditions were established in order to measure the porosity and effective porosity using the DDMs (dielectric mixing models). This study also included estimating fully saturated conditions using the back pressure method, determining the physical porosity by oven dry test, keeping constant in-door temperature at 20 °C, and confining the degree of corrective relative dielectric constant of pure materials such as water, sand, ethanol 95 %. These were carried out to arrive at accurate the effective porosities of the fully saturated sands. During all experiments, the concentration of the ethanol tracer materials had tendency to slowly decrease with travel time, which measured about 20 – 30 % of the initial tracer concentration.

The sensitivity of the relative dielectric constant at 1 GHz by measured FDR and FDR-V systems show to be measured a similar feature, which determined about 27 to 38 for the initial relative dielectric constant with each estimated porosity - 0.35, 0.40 and 0.45. However, the final relative dielectric constant was little different: soil column injection test with the FDR and FDR-V systems represented to the range of nearly 9 to 12 by 95 % ethanol liquid. The discrepancy of initial and final dielectric constants for injection tests is considered to the variation of ethanol concentration of tracer materials as pure ethanol 95 %.

From the results of the DDMs study, the mean effective porosity of the Toyoura and River sands were 0.344, 0.347 and 0.333. Their corresponding mean physical porosities were 0.402, 0.411 and 0.395, respectively. Therefore, the ratio of effective porosity to porosity of Toyoura and River sands were 0.856 and 0.843. The relationship between the relative porosities and the relative effective porosities, all measured values can be confirmed to outside the range about 0.80 for Toyoura and River sands under all experiments by FDR and FDR-V systems. In the case of both of the relative porosities, the measured porosity by DDMs can be easily generated to be the deviations due to the effect of an initial relative dielectric constant when a measuring probe was inserting into the fully saturated sand. Considering these deviations of them, the physical porosity measured from the oven dry test can be derived to be a similar value with them. Furthermore, the measured effective porosities for soil column injection and replacement tests represented within the limits of nearly 88 % from comparing of a 1:1 fixed scale. These differences were considered to be related of the sensitivity of measured relative dielectric constant under fully saturated sands by two systems.

The above results were obtained from the relationship that exists between effective porosity and the relative dielectric constant determined with the FDR and FDR-V systems. Therefore, the physical parameters such as porosity, effective porosity, volumetric water content, and degree of saturation of the soils can be determined easily and quickly from the relative dielectric constants obtained from both systems. In the laboratory experiments, this apparatus equipment can be considered to be effective enough to measure determining the physical parameters effective porosity of fully saturated soils. Consequently, this permittivity method can be contributed to estimate a porosity and effective porosity of fully saturated porous media because it is easily and instantaneously than previous in-situ methods.

Further works are however recommended to be undertaken, in order to determine the applicability of the systems in other soils and with other tracers, especially in in-situ determinations. As base on these results and measuring methods, it is necessary to new measuring experimental methods, and an improvement of measuring probe and system as well as development of tracer material for application of in-situ site.

References

Campbell, J.D., 1973, Pore pressures and volume changes in unsaturated soils, Ph.D. thesis, University of Illinois, Urbana, Illinois.

Chenaf, D., and Amara, N., 2001, Time domain reflectometry for the characterization of diesel contaminated soils, TDR 2001: Innovative Applications of TDR Technology, Infrastructure Technology Institute, Northwestern University, Evanston, IL, September,2001.

Curtis, H.L. and F.M Defandorf, 1929, Dielectric constant and dielectric strength of elementary substances pure inorganic compounds, and air. In: Washburn, E.D. (Ed.), International Critical Tables of Numerical Data, Physics, Chemistry and Technology, vol. 6. McGraw-Hill, New York, 73-107.

Drnevich, V. P., Siddiqui, S. I., Lovell, J., and Yi, Q., 2001, Water content and density of soil in situ by the purdue TDR method, TDR 2001: Innovative Applications of TDR Technology, Infrastructure Technology Institute, Northwestern University, Evanston, IL, September, 2001.

Head, K.H., Manual of soil laboratory testing. Vol. 1: Soil classification and compaction test, London, Pentech Press, 1980.

Jacobsen, O.H. and P. SchjØnning, 1993, A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture, Journal of Hydrology, 151, 147-157.

Jones, S. B., and Or, D., 2001, Frequency-domain methods for extending TDR measurement range in saline soils, TDR 2001: Innovative Applications of TDR Technology, Infrastructure Technology Institute, Northwestern University, Evanston, IL, September, 2001.

Kim, J. Y., T. B. Edil and Park, J. K., 1997, Effective porosity and seepage velocity in column tests on compacted clay, Journal of geotechnical and geoenvironmental engineering, Vol. 123(12), 1135-1142.

Li, H., Y. Ohtsuka, N. Mori, T. Inagaki and S. Misawa, 1996, Effective porosity and specific yield of a sedimentary rock determined by a field tracing test using tritium as a tracer, Environmental Geology, Vol 27(3), 170-177.

Rassam, D. W. and D. J. Williams, 1997, Application of time domain reflectometry to mine waste rehabilitation, GeoEnvironment 97, Bouazza, Kodikara & Parker (eds), 433-438.

Shackelford, C. D., 1994, Critical concepts for column testing, Journal of Geotechnical Engineering, Vol. 120(10), 1804-1828.

Shackelford, C. D. and P. L. Redmond, 1995, Solute breakthrough curves for processed kaolin at low flow rates, Journal of Geotechnical Engineering, Vol. 121(1), 17-32.

Singh, S. K., 2002, Estimating dispersion coefficient and porosity from soil-column tests, Environmental Microbiology, Vol 128(11), 1095-1099.

Tada, H., 1994, Study on the infiltration characteristics of the clay soils, Muster thesis, Okayama University, Japan. (In Japanese).

Tonder, G. V., K. Riemann and I. Dennis, 2002, Interpretation of single-well tracer tests using fractional-flow dimensions. Part 1: Theory and mathematical models, Hydrogeology Journal, 2002

Topp, G. C., Davis, J. L., and Annan, A. P., 1980, Electromagnetic determination of soil water content: Measurements in coaxial transmission lines, Water Resour. Res., 16(3), 574-582.

Wilson, L. G., L. G. Everett and S. J. Cullen, 1995, Handbook of vadose zone characterization & monitoring: Part V- Preliminary monitoring-related activities (Ch. 12), Lewis Publishers, USA, 177-188.

Zheng, Z., P. Aagaard and G. D. Breedveld, 2002, Sorption and anaerobic biodegradation of soluble aromatic compounds during groundwater transport. 1. Laboratory column experiments, Environmental Geology, 41, 922-932.