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Field Estimation of Soil Dry Bulk Density Using Amplitude Domain Reflectometry Data

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Abstract

Since permeability of field soils is strongly affected by dry bulk density, knowledge of spatial distribution of dry bulk density is beneficial to predict water and chemical transport through soils. In this study, field soil dry bulk density was estimated by using Amplitude Domain Reflectometry (ADR) data. The experiment was sited at the Sakae-cho experimental field of Tokyo University of Agriculture and Technology (TUAT) covered by Andisol soil. The field of 4 ×4 m in large was divided into 81 small plots of 0.5×0.5 m each. The ADR probe was operated in every small plot, and the ADR output voltage was measured by using digital voltmeter. Soil samples were taken by using the steel ring of 100 cm^3 in volume. The results showed that the estimated dry bulk density agreed well with the measured dry bulk density. The regression coefficient (R^2) ranged from 0.4 to 0.7. Dry bulk density estimated by using the ADR data and wet bulk density (R^2=0.5–0.7) had greater accuracy than that by using the ADR data and mass wetness (R^2=0.4–0.6). Furthermore, spatial variability, which was expressed by semivariogram, of the measured and the estimated dry bulk density by using the ADR data and wet bulk density agreed well. However, spatial variability of the dry bulk density estimated by using the ADR data and mass wetness showed different trend to others. This indicated that the estimated dry bulk density with wet bulk density had better performance to predict dry bulk density than that with mass wetness.

Key words : Dry bulk density, ADR, Andisol, Spatial variability, Semivariogram

1. Introduction

Field soil physical properties are quite variable, both in vertical and horizontal directions. Beside, these properties also vary with time. Since soil physical properties play a central role in transport and reaction of water, solutes, and gases in soils, knowledge of spatial variability of soil physical properties is very important for understanding transport phenomena in soils, hence, for soil conservation and planning appropriate agricultural practices. More specifically, knowing field soil dry bulk density would help in scaling other important soil physical properties, i.e., predicting soil permeability as a function of dry bulk density by using non-similar media concept (NSMC) method (Miyazaki, 1996). The soil permeability data can be used to determine the better K factor of Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). However, measurement of the field-spatially-distributed soil parameters tends to be difficult and complicated, such as time consuming, laborious and expensive (Zorita *et al.,* 2001). Therefore, the use of a proper method to measure field soil physical properties with low cost, simple and quick method is required.

Amplitude Domain Reflectometry (ADR) probe is one of the methods for measuring

Table 1 Soil physical properties

Soil parameters	First field experiment (Sakae-cho soil)		Second field experiment (Sakae-cho soil)	
Texture (kg kg^{-1}) : sand	0.29	Light Clay (LiC)	0.29	Light Clay (LiC)
silt	0.37		0.37	
clay	0.34		0.34	
Mass wetness, w (%)	60–93		60–88	
Dry bulk density, ρ_b (g cm^{-3})	0.49–0.66		0.49–0.68	
Volumetric water content, θ (cm^3 cm^{-3})	0.35–0.52		0.36–0.52	

volumetric soil water content based on measurement of dielectric constant of the soil (Gaskin and Miller, 1996 ; Robinson *et al.,* 1999 ; Inoue, 1998a, 1998b ; Nakashima *et al.,* 1998). The ADR probe has a similar performance to other permittivity methods, such as Capacitance Insertion Probe (CIP) and Time Domain Reflectometry (TDR) probe (Miller and Gaskin, 1996 ; Nakashima *et al.,* 1998). However, the ADR probe has advantages over the latter probes, and it is relatively cheaper and simpler automatic measuring system compared to the CIP and the TDR (Nakashima *et al.,* 1998). In other word, since the ADR output is direct current voltage, it can be simply connected to the commercial multi-channel logger to monitor changes in soil water content. Practically, the ADR probe was successfully applied to a project, which tries to investigate the impact of land use changes on catchments behavior, specifically hydrology and hydrochemistry (Miller and Gaskin, 1996).

In recent decades, special attention has been focused on field spatial variability of soil physical properties. Geostatistics, which involves the theory of regionalized variable, is being extensively used to characterize the structure of these variabilities (Tominaga *et al.,* 2002). The regionalized variable is a property such as soil moisture content, dry bulk density, hy draulic conductivity, etc., which can be sampled. Accordingly, the properties (or samples) taken at close spacing will be similar or spatially correlated, while the properties from large sample spacing will be dissimilar or spatially uncorrelated (Isaaks and Srivastava, 1989). The phenomena above can be clearly clarified by using semivariogram as one of the most common geostatistics tools, which can quantify the spatial dependence and spatial structure based on distance of separation and direction (Scot, 2000), and, in turn, it is essential to design of optimal sampling grids and interpolation methods (Isaaks and Srivastava, 1989).

Objective of this presenting study was to estimate the field soil dry bulk density by using the ADR data.

2. Materials and Methods

2.1 Soil Materials

The field experiment was located at the Sakae-cho experimental field of Tokyo University of Agriculture and Technology (TUAT), Japan. The Andisol field of 4×4 m in large was divided into 81 small plots (9 rows and 9 columns) with 0.5×0.5 m each. The physical properties of the soil are shown in Table 1.

2.2 Experimental Procedures

The field experiment was conducted two times, such as in July 2000 (first field experiment) and December 2000 (second field experiment). In each experiment, core samples and the ADR data were collected from every small plot. Soil core samples were taken by using the steel ring of 100 cm^3 in volume. The ADR data were collected by embedding the ADR probe of 60 mm in length into the field soil and the ADR output voltage was measured by using digital voltmeter. The embedding of the ADR probe was replicated three times surrounding the soil core sample location and averaged. To stabilize the ADR output signals, the embedding the ADR probe was kept for 20 to 30 seconds. Since the field contains 81 small plots, the amounts of samples were totally 81 soil core samples and 81 the ADR data for each experiment. All soil core samples were brought to the laboratory and several soil parameters such as mass wetness, wet bulk density, dry bulk density, and volumetric water content were measured by using gravimetric method.

In addition, the first field experiment was conducted on field soil having dry layer at the surface. However, it was expected that the presence of surface dry layer might enhance heterogeneity in soil moisture distribution within the field profile, which affects the ADR performance (Wijaya *et al.,* 2002). To improve the ADR performance, therefore, in the second field experiment, the surface dry layer of a cm in thickness by observation was removed prior to the ADR measurement and the soil core sampling. Such treatment resulted in relatively less heterogeneity in moisture content distribution within the field profile.

2.3 Calculation of Dry Bulk Density with ADR Data

Dry bulk density can be calculated as function of volumetric water content measured by using the ADR probe (θ_{ADR}) combined with either wet bulk density (Eq. (1)) or mass wetness (Eq. (2)),

$$\rho_{best\,1}=\rho_t-(\theta_{ADR}\cdot\rho_w) \quad (1)$$

$$\rho_{best\,2}=\left(100\frac{\theta_{ADR}}{w}\right)\cdot\rho_w \quad (2)$$

where, $\rho_{best\,1}$ is the estimated dry bulk density with wet bulk density (g cm^{-3}), $\rho_{best\,2}$ is the estimated dry bulk density with mass wetness (g cm^{-3}), ρ_t is the wet bulk density (g cm^{-3}), ρ_w is the density of water (=1 g cm^{-3}), θ_{ADR} is the volumetric water content measured by using the ADR probe (cm^3 cm^{-3}), w is the mass wetness (%). Eq. (2) is multiplied with 100 to convert the mass wetness by percentage to that by decimal form.

Application of the ADR method, which involves the use of either Eq. (1) or (2), in estimating dry bulk density from volumetric water content measured by using the ADR probe (θ_{ADR}) offers more benefits compared to traditional oven drying method such as simple, less labor and less time consuming. Wijaya *et al.* (2003) reported that to obtain dry bulk density by using Eq. (1) needs only the information of soil wet mass (weight) occupying the known volume of core sample and it is not necessary to spend a day to oven dry the sample. Also, only a small fraction of the disturbed soil sample, less than 10 grams, which is used to measure mass wetness, is required to estimate the dry bulk density by using Eq. (2). Therefore, the ADR method helps us to perform easy, quick, and less labor determination of field soil dry bulk density, especially when large numbers of data are required.

The θ_{ADR} data, which is substituted into Eq. (1) and (2) was obtained from the third order polynomial equation (Eq. (3)) as a result of calibration between the ADR output voltage and volumetric water content of the Andisol soil (Wijaya *et al.,* 2003). The dry bulk density was ranged from 0.39 to 0.96 g cm^{-3} during the calibration, which was performed on the soil with mass wetness ranged from 40 to 70 %.

$$\theta_{ADR}=0.00111+1.531\mathrm{v}-2.342\mathrm{v}^2+1.448\mathrm{v}^3 \quad (3)$$

where, v is the ADR output voltage (volt).

2.4 Semivariogram

Generally, classical measures of location such as arithmetical mean (M), and spread of data such as standard deviation (Std. Dev.) and coefficient of variation (CV) are used to evaluate statistical characteristics of the sample population, which can be described as the frequency distribution. However, the frequency distribution is somewhat limited in its ability to describe variability of a sampled population because it does not provide any information about spatial correlation between samples at a given location.

To solve the problem above, semivariogram, which can express the degree of spatial dependence between two samples at a given separation distance and direction, has been used to characterize spatial variability of hydraulic conductivity (Mohanty, *et al.,* 1994 ; Ciolarro and Romano, 1995), soil water content and dry bulk density (Tominaga *et al.,* 2002), soil water content and solute concentration (Netto *et al.,* 1999), soil organic matter, NO_3-N, pH and electric conductivity (Imade, *et al.,* 2001). It can be defined as a graph (and/or formula) describing the expected difference in value between pairs of samples with a given relative distance and direction (Clark, 1979). The vertical axis is semivariance, $\gamma(h)$ and the horizontal axes is distance between two data points, h. For one-dimensional data, the $\gamma(h)$ value at given position can be computed by the following equation,

$$\gamma(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}[z(x_i)-z(x_i+h)]^2 \qquad (4)$$

where, $N(h)$ is the number of data pairs separated by the lag interval h, $z(x_i)$ is the measured sample value at point x_i, and $z(x_i+h)$ is the measured sample value at a distance h from x_i.

3. Results and Discussions

3.1 Comparison between Estimated and Measured Dry Bulk Density

Figure 1 shows comparison between the estimated dry bulk density by using Eq. (1) and the measured dry bulk density, including data obtained from the first and the second field experiment. As can be seen from the figure, the estimated and the measured data points were laid on and concentrated around 1 : 1 regression line. It indicated that the ρ_{best} fitted well with the ρ_{bmsr}. The estimated dry bulk density obtained from the second field experiment tended to be more reliable than that from the first field experiment. The regression coefficient (R^2) was 0.674 and 0.466, for the second and the first field experiment, respectively. Correspondingly, the root mean square error (RMSE) value between the ρ_{bmsr} and the ρ_{best} by using Eq. (1) was 0.032 and 0.059 g cm^{-3}, for the second and the first field experiment, respectively.

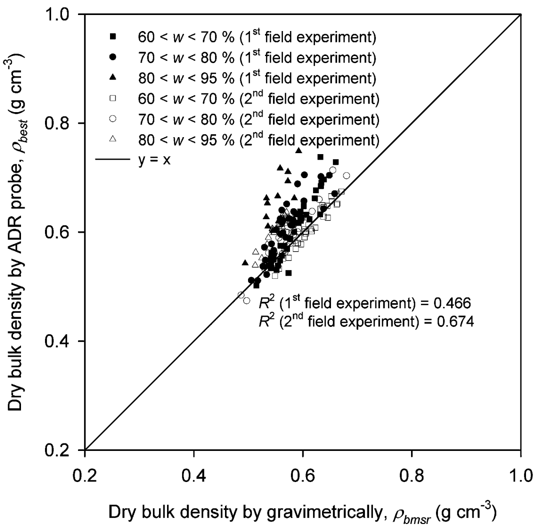


Fig. 1 Comparison between the estimated dry bulk density by using Eq. (1) and measured dry bulk density.

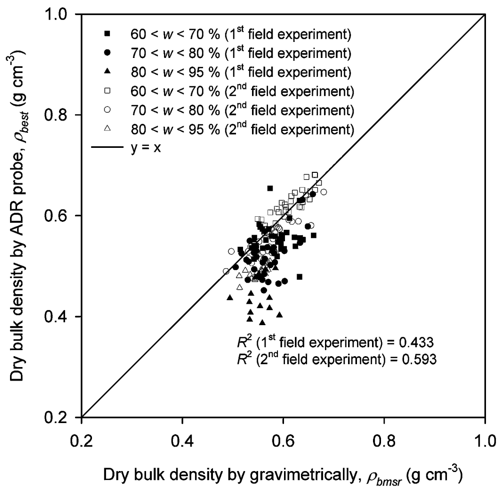


Fig. 2 Comparison between the estimated dry bulk density by using Eq. (2) and measured dry bulk density.

Figure 2 shows comparison between the estimated dry bulk density by using Eq. (2) and the measured dry bulk density, including data from the first and the second field experiment. Unlike the results shown in Fig 1, the estimated and the measured data points shown in Fig 2 were slightly deviated from and scattered around 1 : 1 regression line. It indicated that the ρ_{best} tended to be underestimated and less agreed with the ρ_{bmsr}. The estimated dry bulk density from the second field experiment was better than that from the first field experiment, however, it still showed lower accuracy compared to the results of Eq. (1) as shown in Fig 1. In Fig 2, the R^2 was 0.593 and 0.433, for the second and the first field experiment, respectively. The RMSE value between the ρ_{bmsr} and the ρ_{best} by using Eq. (2) was 0.039 and 0.074 g cm^{-3}, for the second and the first field experiment, respectively.

Difference in accuracy between the estimated dry bulk density obtained from the first and the second field experiment was due to difference in the surface treatment among them. The presence of the surface dry layer of a cm thickness in the first field experiment, which enhanced greater heterogeneity in soil moisture distribution within the field profile, could reduce the ADR performance. The surface dry layer might be produced mainly through evaporation process especially in the bare field soil. Greater the thickness of the dry layer in the soil, greater the vertical heterogeneity in soil moisture distribution within its profile, which, in turn, enhances the error of the ADR output (Wijaya, *et al.*, 2002). The field soil with removal of surface dry layer in which the ADR probe and the core sample was embedded had more uniform in soil moisture distribution than that with a surface dry layer (first field experiment). Therefore, the errors of the ADR output could be reduced when the ADR probe was applied on such soil.

Comparison between the results shown in the Fig 1 and 2 showed that the estimated dry bulk density with the wet bulk density had greater accuracy than that with the mass wetness. Difference in calculation process between

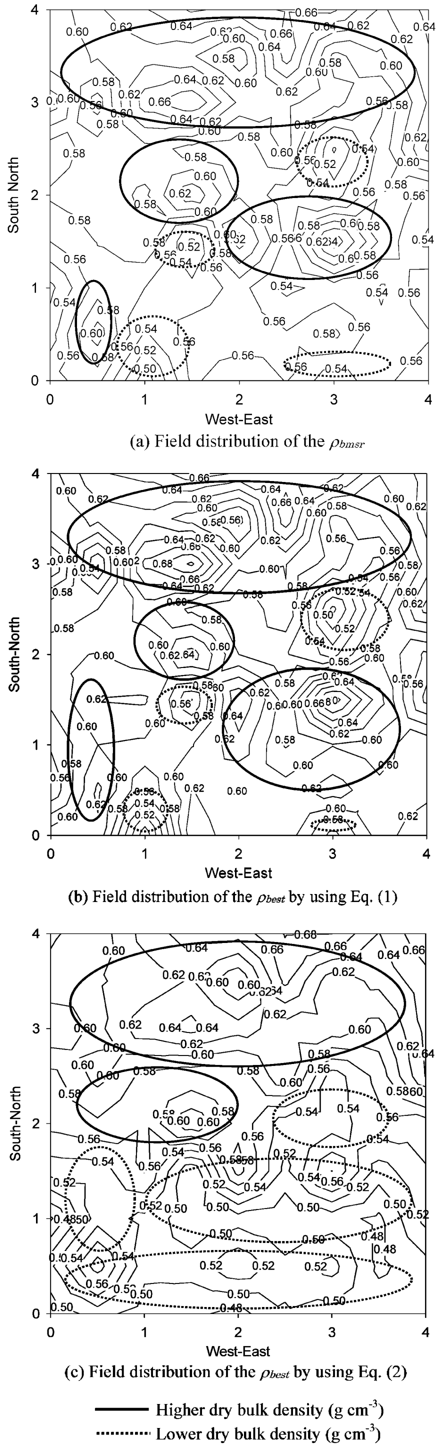


Fig. 3 Field distribution of soil dry bulk density for the second field experiment: (a) the ρ_{bmsr}, (b) the ρ_{best} by using Eq. (1), and (c) the ρ_{best} by using Eq. (2).

Eq. (1) and (2) could be a primary factor affecting the results. The Eq. (2) is a division formula, thus, when the θ_{ADR} containing an error was substituted into this equation, running the division process might increase the error in ρ_{best} since denominator (w) was smaller than unity. This error was relatively greater compared to the case when the θ_{ADR} data were substituted into Eq. (1) (Wijaya *et al.,* 2003). Therefore, the greater accuracy of θ_{ADR} was very important to enhance the greater accuracy of ρ_{best}.

3.2 Field Distribution of Dry Bulk Density

Field distribution of dry bulk density at the second field experiment is shown in Fig 3, which is consisted of (a) measured, (b) estimated by Eq. (1) and (c) estimated by Eq. (2). As can be seen from the figures, the distribution of the cloud of data points for the ρ_{best} was similar with that for the ρ_{bmsr}. The greater values of ρ_b were dominantly contoured around the northern part of the field from west to east, and the middle of the field. The lower values of ρ_b spread out around southern-western part, southern-eastern part and middle of the field. The greater values of ρ_b ranged from 0.58 to 0.68 g cm^{-3}, while the lower values of ρ_b ranged from 0.48 to 0.54 g cm^{-3}.

Degree of similarity between the distribution of the ρ_{best} by using either Eq. (1) or (2) and that of the ρ_{bmsr} are shown in Fig 4 (a) and 4 (b), respectively. According to the figures, the similarity can be simply evaluated by the contour of the square difference in data points between the ρ_{best} and ρ_{bmsr}, which was expressed as the errors of ρ_{best}. The errors of the ρ_{best} by using Eq. (2) (Fig 4 (b)) were greater than that by using Eq. (1) (Fig 4 (a)). The errors ranged from 0.0005 to 0.0055 g cm^{-3} and from 0.0005 to 0.0040 g cm^{-3}, for the ρ_{best} by using Eq. (2) and (1), respectively. These errors were mostly distributed around the southern part of the field from west to east, due to the greater errors of θ_{ADR} at the same area (Fig 5). Since accuracy of the ADR probe is strongly affected by volumetric water content distribution along with sensing rods (Wijaya *et al.,* 2002), it was suspected that some vertical heterogeneity in moisture or dry bulk density might be occurred at southern part of the field. Error distribution of the θ_{ADR} around the northern part was very small, and only small error distribution of the ρ_{best} was encountered at the same location. It indicated that the θ_{ADR} accuracy was an important factor in the estimation of dry bulk density.

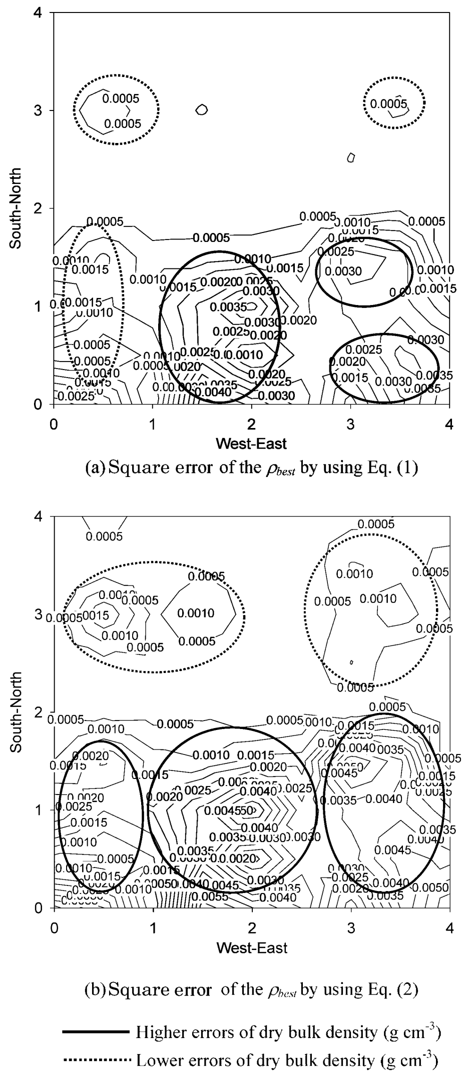


Fig. 4 Square error distribution of the estimated dry bulk density : (a) square error of the ρ_{best} by using Eq. (1), and (b) square error of the ρ_{best} by using Eq. (2).

3.3 Spatial Variability of Dry Bulk Density

Statistical values for the measured and the estimated soil physical properties, including mass wetness, w, measured volumetric water content, θ_{msr}, estimated volumetric water content, θ_{ADR}, measured dry bulk density, ρ_{bmsr} and estimated dry bulk density, ρ_{best} by using either Eq. (1) or (2) are summarized in Table 2. Coefficient of variation (CV) for all the measured and the estimated soil physical properties obtained from the first and the second field experiment ranged from 3.3 to 10.9 %. According to these CV values, all the soil physical properties above were confirmed relatively low variability (Wilding, 1985 ; Scot, 2000). The greater CV values occurred on mass wetness, w, ρ_{best} by using Eq. (2) and θ_{msr}, while the lower CV values occurred on the θ_{ADR}, ρ_{bmsr}, and ρ_{best} by using Eq. (1). From Standard Deviation (Std. Dev.) value, it was also clear that the ρ_{bmsr} and ρ_{best} by using Eq. (1), especially for the second field experiment, were not significantly different and considered to be similar each other. However, the Std. Dev. value for the ρ_{best} by using Eq. (2) was distinctly different to the two previous parameters. It indicated that the ρ_{best} by using Eq. (1) had similar variability with ρ_{bmsr}, while the ρ_{best} by using Eq. (2) did not.

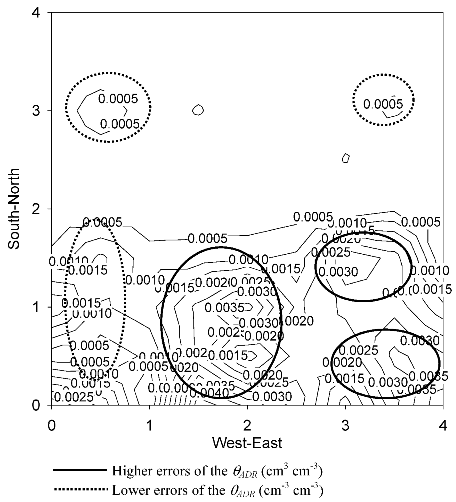
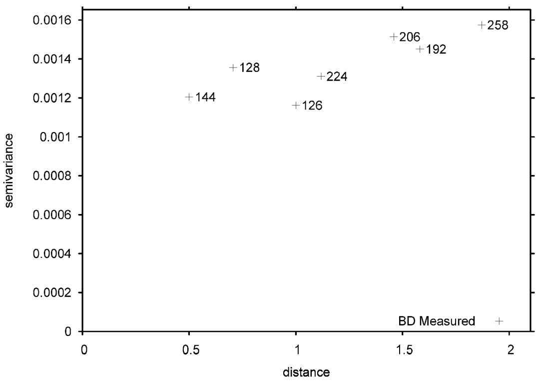


Fig. 5 Square error distribution of the volumetric water content measured by using the ADR data (θ_{ADR}).

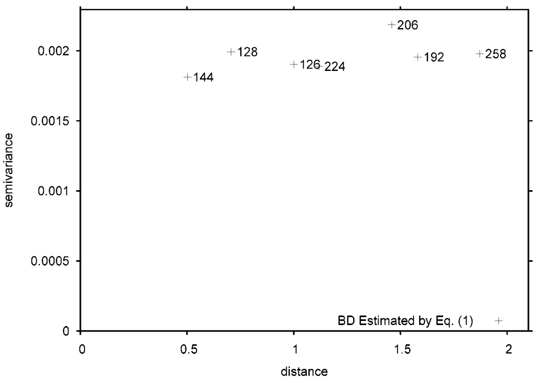
Another aspect in performance of presenting method was discussed by evaluation on spatial variability of the dry bulk density, which was carried out by semivariogram (Fig 6 (a), (b) and (c)). In these three figures, semivariance were plotted within distance between two points ranged from of 0.5 to 2 m. From the trend of semivariance, the ρ_{bmsr} (Fig 6 (a)) and the ρ_{best} by using Eq. (1) (Fig 6 (b)) were similar. Although the ρ_{bmsr} tended to show smaller semivariance, both the ρ_{bmsr} and ρ_{best} by using Eq. (1) showed steady semivariance with increasing distance between two points. It indicated that the ρ_{bmsr} and the ρ_{best} by using Eq. (1) had similar struc-

Table 2 Statistical values for the field soil physical properties

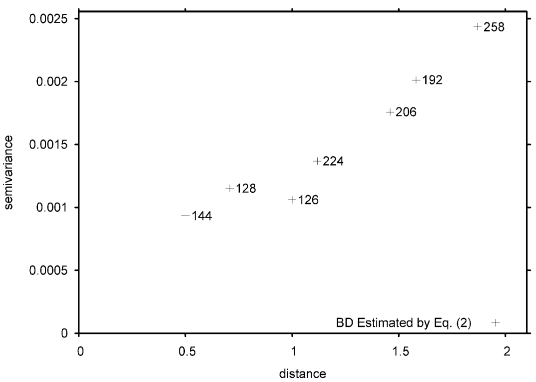
Variables	First field experiment			Second field experiment		
	Mean	Std. Dev.	CV (%)	Mean	Std. Dev.	CV (%)
Mass wetness, w (%)	73.442	7.995	10.89	74.378	7.424	9.98
Measured volumetric water content, θ_{msr} (cm^3 cm^{-3})	0.420	0.045	10.63	0.432	0.033	7.72
Estimated volumetric water content, θ_{ADR} (cm^3 cm^{-3})	0.379	0.031	8.07	0.414	0.014	3.27
Measured dry bulk density, ρ_{bmsr} (g cm^{-3})	0.573	0.036	6.38	0.583	0.042	7.25
Estimated dry bulk density by using Eq. (1), ρ_{best1} (g cm^{-3})	0.614	0.060	9.78	0.600	0.043	7.19
Estimated dry bulk density by using Eq. (2), ρ_{best2} (g cm^{-3})	0.520	0.056	10.68	0.562	0.059	10.64



(a) Semivariogram of the ρ_{bmsr}



(b) Semivariogram of the ρ_{best} by using Eq. (1)



(c) Semivariogram of the ρ_{best} by using Eq. (2)

Fig. 6 Semivariogram of the measured and estimated dry bulk density : (a) semivariogram of the ρ_{bmsr}, (b) semivariogram of the ρ_{best} by using Eq. (1), and (c) semivariogram of the ρ_{best} by using Eq. (2) (numbers in the figures are the number of data pairs for a given lag interval h).

ture of spatial distribution over space. However, the semivariogram of ρ_{best} by using Eq. (2) (Fig 6 (c)) monotonously increased with increasing distance between two points and did not reach a constant value. Results above suggested that the characteristic of spatial distribution of the ρ_{bmsr} agreed well with that of the ρ_{best} by using Eq. (1) and did not agree with that of ρ_{best} by using Eq. (2).

4. Conclusions

Application of the ADR data on estimation of field dry bulk density showed good results. The ρ_{best} by using Eq. (1), combined with wet bulk density data, was better than that by using Eq. (2) with mass wetness. Furthermore, since higher uniformity in soil moisture distribution can reduce the errors of the ADR probe measurement, the second field experiment involving removal of the surface dry layer yielded the greater accuracy of dry bulk density estimation compared to the first field experiment, which was conducted with a surface dry layer.

According to the results of semivariogram, it was found that characteristic of spatial distribution of the ρ_{best} by using Eq. (1) was similar to that of the ρ_{bmsr}. However, the ρ_{best} by using Eq. (2) showed different structure of spatial variability to that of the ρ_{bmsr} and the ρ_{best} by using Eq. (1). Therefore, Eq. (1) was expected to be useful to estimate soil dry bulk density.

This method can serve reasonable quality of dry bulk density data with saving either time or amount of soil sample. Employing Eq. (1) can estimate dry bulk density by taking and weighing sample in situ, while using Eq. (2) requires taking less than 10 grams of soil sample for a dry bulk density data. For some purpose, i.e. taking large number of dry bulk density data for vast area, this method may partly substitute traditional oven drying method with undisturbed sample which requires labor and be time consuming.

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ADR 水分計のデータを用いた不かく乱土壌の乾燥密度推定に関する研究

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要　　旨

ADR 水分計で測定した体積含水率と湿潤密度または含水比を用いて不かく乱土壌の乾燥密度の推定を試みた。実験は東京農工大学栄町圃場で 2 回行った。50 cm 間隔で 9×9 の格子状の点で不かく乱土壌のサンプリングと ADR 水分計の測定を行った。2 回目の実験では地表面の乾燥層（約 1 cm）を除去してからサンプリングならびに測定を行った。乾燥密度の推定値は相関係数（R^2）が体積含水率と湿潤密度を用いた推定値が 0.5 から 0.7, 含水比と体積含水率を用いた推定値が 0.4 から 0.6 と実測値とかなり良く一致した。ADR 水分計の測定値と炉乾燥による実測値の差と併せて考察すると，ADR 水分計の精度が乾燥密度推定の精度に影響することがわかった。また，地表面の乾燥層の有無が ADR 水分計の精度に影響を与えさらには乾燥密度の推定精度に影響することがわかった。セミバリオグラムを求めたところ，ADR 水分計データと湿潤密度を使って推定した乾燥密度は実測値と同様の空間分布特性を持っていた。以上の結果から，ADR 水分計と湿潤密度を用いた不かく乱土壌の乾燥密度推定はかなりよい結果を与えると考えられる。

キーワード : 乾燥密度，誘電率，ADR，火山灰土壌，体積含水率

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