J. Jpn. Soc. Soil Phys.
土壌の物理性
No. 95, p. 63～73 (2003)

Estimation of Dry Bulk Density of Soils Using Amplitude Domain Reflectometry Probe

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Abstract

It is worthy to know the distribution of soil physical properties in the field to gain better understanding of soil behavior. However, taking undisturbed core samples in situ is usually laborious and time consuming. In this study, estimation of dry bulk density of soil by using Amplitude Domain Reflectometry (ADR) data was conducted. The dry bulk density can be calculated by combining volumetric water content measured by using the ADR probe (θ_{ADR}) with either wet bulk density or mass wetness. Andisol (TUAT soil) and Alluvial soil (Fukaya soil, Saitama) was used in this study. Soils were sieved through 3 mm mesh screen, and packed into a plastic acrylic cylinder of 68 mm in inner diameter and 69 mm long. Mass wetness ranged from 40-70% and 15-30%, and packing dry bulk density ranged from 0.39-0.96 g cm^{-3} and 0.78-1.30 g cm^{-3}, for the TUAT and the Fukaya soil, respectively. Three replicated ADR readings of output voltage were measured by using a digital multimeter. The θ_{ADR} was calculated by using a calibrated polynomial equation, as a function of the averaged output voltage. The results showed that the output voltage was not affected by neither packing dry bulk density nor mass wetness. The estimation of dry bulk density with wet bulk density (R^2 value = 0.989-0.994, RMSE value = 0.010-0.014 g cm^{-3}) was better than that with mass wetness (R^2 value = 0.913-0.961, RMSE value = 0.027-0.038 g cm^{-3}). The accuracy of the θ_{ADR} was a critical factor in estimating dry bulk density.

Key words : dry bulk density, ADR, dielectric constant, Andisol, volumetric water content

1. Introduction

Soil behavior generally changes with time and be different from place to place depending on physical condition of soil. Many of soil processes such as physical, chemical, and biological processes are strongly affected by the heterogeneity of soil physical properties. Therefore, understanding of how the soil physical properties distribute in the field is very important for solving soil problems such as irrigation scheduling, drainage, soil and water conservation, nutrient transport, and soil and groundwater contamination.

Dry bulk density of the soil, which can be expressed as the ratio of the mass of dry solids to the bulk volume of the soil (Foth, 1990 ; Hillel, 1998) is one of the most useful soil parameter and a widely used value for predicting other soil physical properties (Culley, 1993). According to Campbell (1985), Miyazaki (1996), and Zhuang *et al.* (2000), dry bulk density can be used to estimate soil permeability, since it strongly affects pore structure, which may dominate soil hydraulic conductivity. The gravimetrical method, which involves weighing and drying a sample of known volume taken from the field, has been commonly used for determination of soil dry bulk density. However, the method is laborious and time-consuming. Therefore, the use of the alternative technique, which is simple and fast for measuring soil dry bulk density, is needed.

Dielectric constant techniques for estimating volumetric water content of soil such as Capacitance Insertion Probe (CIP), Time Domain Reflectometry (TDR) probe, and Amplitude Domain Reflectometry (ADR) probe are becoming popular (Topp *et al.,* 1980 ; Gaskin and Miller, 1996 ; Inoue, 1998 a, 1998 b ; Robinson *et al.,* 1999). These techniques depend on the fact that the dielectric constant of water (～80) is significantly greater than that of most soil matrix materials (～4) and of air (～1). Although the CIP, TDR and ADR probe have a similar performance (Nakashima *et al.,* 1998), the ADR and the TDR probe are easier to install and facilitate the accumulation of data than the CIP, which requires the permanent installation access tubes and operator intervention to position of the sensing head within these tubes (Gaskin and Miller, 1996). Some problems in the data interpretation and the field calibration may be obscured by inhomogeneities around probe wire such as voids and stones, and confused by conductivity effect (Whalley, 1993). Furthermore, the TDR probe and the CIP have some disadvantages of high cost and their complex automatic measuring system (Nakashima *et al.* 1998). On the other hand, the ADR probe is relatively cheap and the output is direct current voltage, which can be measured by commercial multichannel logger to monitor change in water content (Gaskin and Miller, 1996). The ADR probe has been developed to solve the problems of the CIP and TDR probe (Nakashima *et al.,* 1998).

The objective of this study was to apply the ADR technique for estimation of the dry bulk density of disturbed soils.

2. Materials and Methods

2.1 ADR Probe Components

According to Miller and Gaskin (1996), there are three major components of the ADR probe including an input and output cable, probe body, and a sensing head (Fig. 1). The cable provides connection for a suitable power supply (5–15 volt) and for an analogue signal output. The probe body contains an oscillator, a specially designed internal transmissions line and measuring circuitry within a waterproof housing. The sensing head has an array of four electrodes of 60 mm in length and 3 mm in diameter with a radial spacing of 15 mm, the outer three of which connected to instrument ground from an electrical shield around the central (signal) electrode.

Principally, the ADR probe applies a 100 MHz sinusoidal signal via a specially designed internal transmission line to a sensing array of four electrodes whose impedance depends on dielectric constant of water content of the soil into which it is embedded. If this impedance differs from that of the internal transmission line, then a proportion of the signal is reflected back from the junction (J), which lies between the sensing array and the transmission line. This reflected component interferes with the incident signal causing a voltage standing wave to be set up on the transmission line, i.e. a variation of voltage amplitude along the length of the line. Once the amplitude is measured, the relative impedance of the probe and then the dielectric constant will be known. Hence, the volumetric water content of the soil matrix can be obtained.

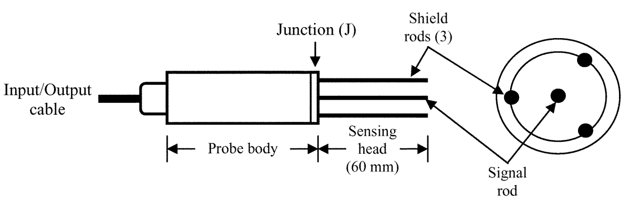

Fig. 1 A schematic diagram of the ADR probe.

2.2 Soil Materials

Two soils such as Andisol (TUAT soil) and Alluvial soil (Fukaya soil) were used in this study. The soils were sieved through a 3 mm mesh screen. A half of the soils were kept in plastic bag to keep mass wetness of 55% and 27%, and the remaining soils were air-dried until mass wetness of 40% and 16%, for the TUAT and the Fukaya soil, respectively. Physical properties of the soils including texture, mass wetness (%), dry bulk density (g cm^{-3}), volumetric water content (cm^3 cm^{-3}) and clay mineral (X ray diffraction) are summarized in Table 1.

2.3 Experimental Methods

To cover the range of soil mass wetness between 40–70% for the TUAT soil and 15–30% for the Fukaya soil, the air-dried sieved soils were moistened with spraying distilled water for four to six times. Each moistened sample was packed into a plastic acrylic cylinder of 68 mm in inner diameter and 69 mm long as uniformly as possible by manually increasing the increments of a few centimeter thickness of the soil to the cylinder up to the full volume. The sample was then weighted by using an electric balance to obtain wet bulk density.

The ADR probe was vertically inserted into the sample (Fig. 2). The ADR reading of output voltage was then measured by using a digital multimeter. Three replicated ADR readings were taken by re-installing the ADR probe vertically into an undisturbed part of the cylinder and then averaged. After the ADR operation, a sub-sample was taken and oven-dried to determine mass wetness. Measured volumetric water content and dry bulk density were calculated from the mass wetness and the wet bulk density.

The whole procedure was repeated for packing dry bulk density ranged from 0.39–0.96 g cm^{-3} and 0.78–1.30 g cm^{-3} for the TUAT and the Fukaya soil, respectively. The ADR measurement was also applied on the oven-dried samples whose volumetric water content was considered to be zero. To prevent the excess evaporation from the samples during the procedure, the experiment was done inside a small chamber covered with a plastic film.

2.4 Estimation of Dry Bulk Density by Using ADR Probe Data

For the estimation purpose, 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)).

$$\rho_{best1} = \rho_t - (\theta_{ADR} \times \rho_w) \quad (1)$$

$$\rho_{best2} = (100 \times \theta_{ADR} / w) \times \rho_w \quad (2)$$

where, ρ_{best1} is the estimated dry bulk density with wet bulk density (g cm^{-3}), ρ_{best2} 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}), and w is the mass wetness (%). Especially, Eq. (2) was multiplied with 100 to convert the mass wetness by percentage to that by decimal form.

Table 1 Soil physical properties

Soil parameters	Andisol soil (TUAT soil)	Alluvial soil (Fukaya soil)
Texture (kg kg^{-1})	sand : silt : clay = 0.320 : 0.324 : 0.356 (LiC)	sand : silt : clay = 0.460 : 0.320 : 0.220 (CL)
Mass wetness, w (%)	40–70	15–30
Dry bulk density, ρ_b (g cm^{-3})	0.39–0.96	0.78–1.30
Volumetric water content, θ (cm^3 cm^{-3})	0.22–0.64	0.16–0.35
Clay mineral (by X ray diffraction)	amorphous	Kr > Vr > Mi, Sm

The use of either Eq. (1) or (2) in estimating dry bulk density from the volumetric water content measured by using the ADR probe (θ_{ADR}) gives some advantages especially when it is applied to the field measurement. For example, to obtain the estimated dry bulk density by using Eq. (1) needs only the information of the wet mass (weight) of the soil occupying the known volume of the core sample, and it is not necessary to spend a day for oven drying the sample. It helps us to perform easy and fast estimation of field dry bulk density, especially when the large numbers of data are required. Furthermore, although obtaining the mass wetness data spends more time than the wet bulk density because of the need to oven drying the sub-sample, incorporating the mass wetness to Eq. (2) is still reasonable. For example, when the estimation of the dry bulk density is applied on taking larger numbers of field data, the mass wetness can be obtained by oven drying the only a small fraction of disturbed sample, so that it is capable to perform number of estimation with less labor.

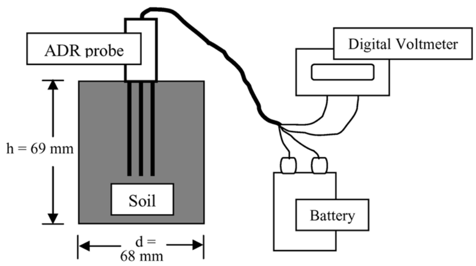

Fig. 2 Schematic diagram of the experiment.

3. Results and Discussions

3.1 Relationship between Volumetric Water Content and Output Voltage

The calibration curve of the volumetric water content and the output voltage for the TUAT soil shows increase in output voltage with increasing in volumetric water content (Fig. 3). The output voltage ranged from 0.16–0.99 volt corresponded to volumetric soil water content of 0.22–0.64 cm^3 cm^{-3}. The relationship between output voltage and volumetric water content can be expressed in Eq. (3) with regression coefficient (R^2) value of 0.984,

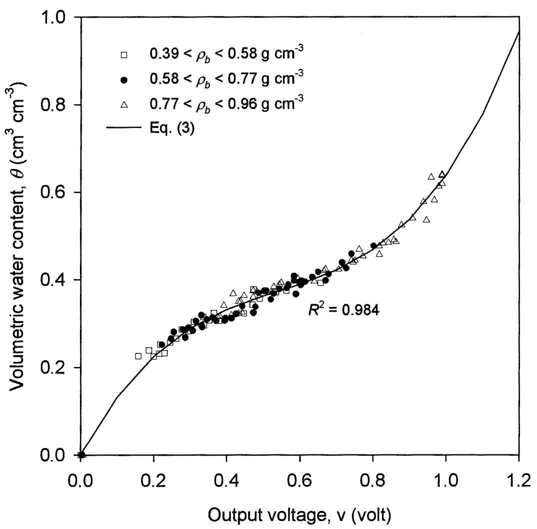

Fig. 3 (a) Relationship between volumetric water content and ADR output voltage for the TUAT soil, in case of packing dry bulk density.

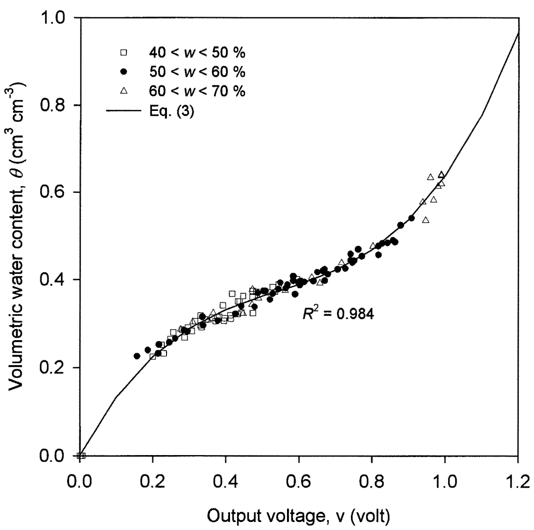

Fig. 3 (b) Relationship between volumetric water content and ADR output voltage for the TUAT soil, in case of mass wetness.

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

where, v is the output voltage of the ADR probe. Mathematical expression shown in Eq. (3), (4), (6) and (7) are the third polynomial equations which were accomplished by applying least square method.

Increasing the output voltage with the increasing in volumetric water content was also found in the Fukaya soil (Fig. 4). The soil with volumetric water content ranged from 0.16–0.35 $cm^3\,cm^{-3}$ corresponded to the output voltage of 0.22–0.86 volt, and the relationship between output voltage and volumetric water content can be expressed in Eq. (4) with R^2 value of 0.981.

$$\theta_{ADR} = 0.00335 + 0.964v - 1.530v^2 + 1.038v^3 \quad (4)$$

The θ-v curve shown in Fig. 3 and 4 contains two cases such as either packing dry bulk density or mass wetness as a parameter. Each case is divided into three data intervals. For the TUAT soil, the packing dry bulk density ranged from 0.39–0.58, 0.58–0.77, and 0.77–0.96 g cm^{-3} and the mass wetness ranged from 40–50, 50–60, and 60–70%, respectively. For Fukaya soil, the packing dry bulk density ranged from 0.78–0.95, 0.95–1.13, and 1.13–1.30 g cm^{-3} and the mass wetness ranged from 15–20, 20–25, and 25–30%, respectively. Although dry bulk density of the TUAT soil was smaller than that of the Fukaya soil, the TUAT soil had greater mass wetness. It was due to micro structure of the TUAT soil (Light Clay) was more complicated than the Fukaya soil (Clay Loam). As a consequence, the TUAT soil was capable to retain more water per unit weight of the soil than the Fukaya soil.

The division of the packing dry bulk density and the mass wetness into three data intervals was aimed to clarify the dependence of the output voltage against the two parameters. As shown in Fig. 3 and 4, the plotted data overlapped through the regression line within those three data intervals. It suggested that the output voltage was not affected by neither packing dry bulk density nor mass wetness. The root mean square error (RMSE) value between the measured θ and the θ_{ADR} of whole data with different packing dry bulk density

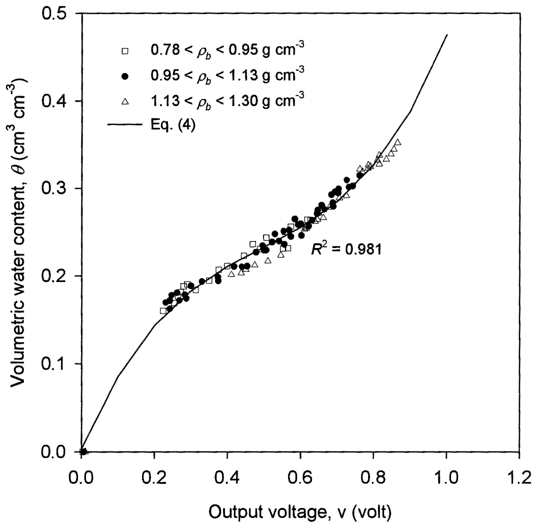

Fig. 4 (a) Relationship between volumetric water content and ADR output voltage for the Fukaya soil, in case of packing dry bulk density.

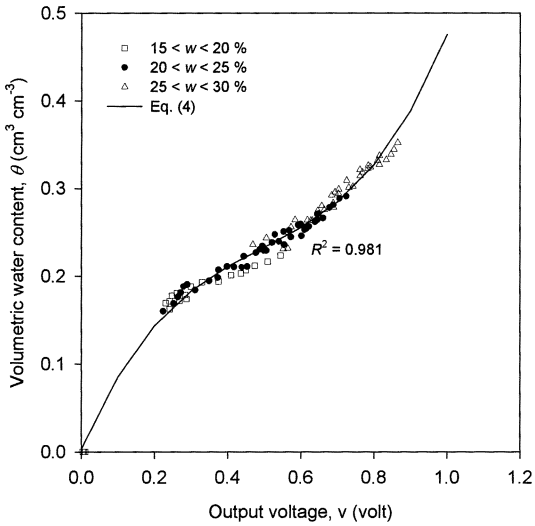

Fig. 4 (b) Relationship between volumetric water content and ADR output voltage for the Fukaya soil, in case of mass wetness.

and mass wetness was 0.014 $cm^3 cm^{-3}$ and 0.008 $cm^3 cm^{-3}$ for the TUAT and the Fukaya soil, respectively. It revealed that the θ_{ADR} significantly depended on the type of soil. The independence of the θ_{ADR} on either packing dry bulk density or mass wetness was also clarified by the RMSE value of each interval of the parameters. In case of the TUAT soil, the RMSE value for packing dry bulk density ranged from 0.39–0.58, 0.58–0.77, and 0.77–0.96 g cm^{-3} was 0.014, 0.013, and 0.016 $cm^3 cm^{-3}$, while that for mass wetness ranged from 40–50, 50–60, and 60–70% was 0.015, 0.012, and 0.017 $cm^3 cm^{-3}$, respectively. Furthermore, in case of the Fukaya soil, the RMSE value was 0.007, 0.008, and 0.010 $cm^3 cm^{-3}$ for packing dry bulk density ranged from 0.78–0.95, 0.95–1.13, and 1.13–1.30 g cm^{-3}, and 0.012, 0.006, and 0.009 $cm^3 cm^{-3}$ for mass wetness ranged from 15–20, 20–25, and 25–30%, respectively.

3.2 Relationship between Volumetric Water Content and Dielectric Constant

Miller and Gaskin (1996) found that in the range of output voltage of 0–1 volt, the relationship between the ADR reading of output voltage and the square root dielectric constant can be precisely described by the third polynomial equation, as shown in Eq. (5). In this study, the equation was employed for the TUAT and the Fukaya soil.

$$\sqrt{\varepsilon} = 1.07 + 6.40\text{v} - 6.40\text{v}^2 + 4.70\text{v}^3 \qquad (5)$$

where, $\sqrt{\varepsilon}$ is the square root dielectric constant.

Since the volumetric soil water content was the primary factor affecting the apparent dielectric constant, increasing volumetric water content resulted in the increase of the dielectric constant (ε), as shown in Fig. 5 and 6. For the TUAT soil (Fig. 5), in the range of the dielectric constant of 4–32, which corresponded to the volumetric water content of 0.22–0.64 $cm^3 cm^{-3}$, the relationship can be expressed in Eq. (6).

$$\theta_{ADR} = 0.195 + 0.0265\varepsilon - 0.000984\varepsilon^2 + 0.0000183\varepsilon^3 - 0.275\varepsilon^{-1} + 0.00625\varepsilon^{-2} \qquad (6)$$

The dielectric constant of the Fukaya soil ranged from 5–24 corresponded to the volumetric water content of 0.16–0.35 $cm^3 cm^{-3}$, as shown in Fig. 6. The following Eq. (7) expressed the relationship between volumetric water content and dielectric constant for the Fukaya soil.

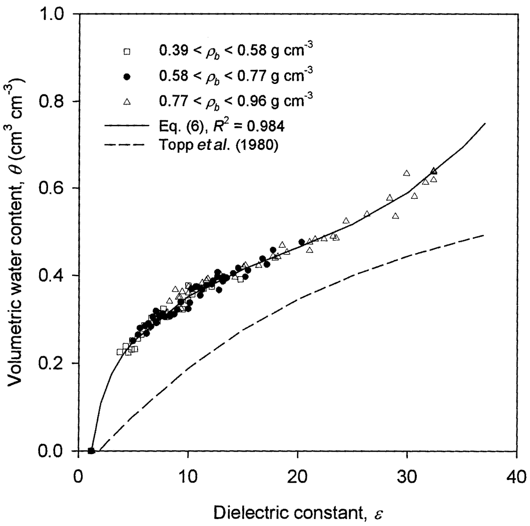

Fig. 5 Relationship between volumetric water content and dielectric constant of the TUAT soil.

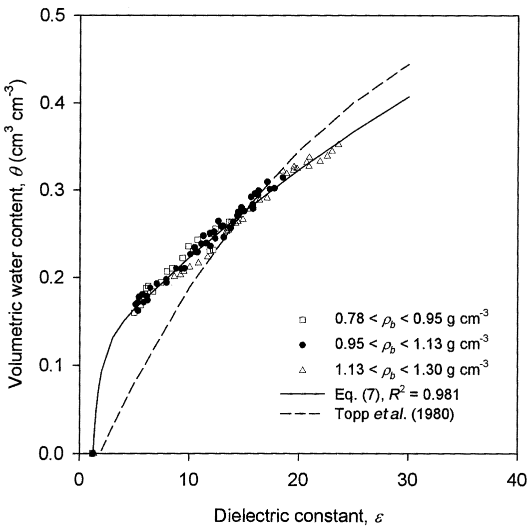

Fig. 6 Relationship between volumetric water content and dielectric constant of the Fukaya soil.

$$\theta_{ADR}=0.0974+0.0129\varepsilon-0.0000916\varepsilon^2+0.0744\varepsilon^{-1}-0.265\varepsilon^{-2} \quad (7)$$

Topp *et al.* (1980) presented the "universal calibration formula" for measuring volumetric water content based on dielectric constant of many (common) soils in all over the world, as shown in Eq (8).

$$\theta=-0.053+0.0292\varepsilon-0.00055\varepsilon^2+0.0000043\varepsilon^3 \quad (8)$$

Comparison between the Topp's universal equation and the equations derived from the θ-v calibration of the two Japanese soils in this study showed that the dielectric constant of the TUAT soil was significantly greater than that of the Topp's soils, while for the Fukaya soil, it was rather similar to the data presented by Topp *et al.* (1980) and was higher only when volumetric water content was 0–0.2 $cm^3 cm^{-3}$. It suggested that the universal equation was not always applicable for measuring volumetric water content of the soils such as the TUAT soil. For the Fukaya soil, Topp's equation was rather acceptable especially for volumetric water content ranged from 0.25–0.33 $cm^3 cm^{-3}$. These trends were similar to the results presented by Miyamoto and Chikushi (2000). Also, Fig. 5 and 6 revealed that dielectric constant was strongly affected by the type of soil.

3.3 Comparison between Estimated and Measured Dry Bulk Density

Since the estimated dry bulk density (ρ_{best}) was calculated by substituting the θ_{ADR} data obtained from Eq. (3) and (4) into Eq. (1) and (2), the accuracy of the ρ_{best} was strongly affected by the accuracy of the θ_{ADR} data. In case of the TUAT soil, the accuracy of the ρ_{best} can be determined from the comparison between the ρ_{best} and the measured dry bulk density (ρ_{bmsr}) shown in Fig. 7. The figure describes that the ρ_{best} agreed well with the ρ_{bmsr}. The cloud of the data points was laid and concentrated around the 1 : 1 regression line. The R^2 value for the data estimated by using Eq. (1) and (2) were 0.989 and 0.961, respectively. It revealed that the estimation of dry bulk density with wet bulk density had greater accuracy than that with mass wetness. The greater the accuracy of the ρ_{best}, the lower the error of the ρ_{best}. In this study, the error is expressed in the RMSE value between the ρ_{bmsr} and the ρ_{best}. For whole data, the RMSE value of the ρ_{best} by using Eq. (1) was generally a half of that by using Eq. (2) such as 0.014 $g\ cm^{-3}$ and 0.027 $g\ cm^{-3}$, respectively. The RMSE value within the given ranges of packing dry bulk density and mass wetness were fluctuated. In the range of packing dry bulk density of 0.39–0.58, 0.58–0.77, and 0.77–0.96 $g\ cm^{-3}$, the RMSE value of the ρ_{best} by using Eq. (1) was 0.014, 0.013, and 0.016 $g\ cm^{-3}$, and that by using Eq. (2) was 0.024, 0.027, and 0.029 $g\ cm^{-3}$, respectively. In the range of mass wetness of 40–50, 50–60, and 60–70%, the RMSE value of the ρ_{best} by using Eq. (1) was 0.015, 0.012, and 0.017 $g\ cm^{-3}$, and that by using Eq. (2) was 0.034, 0.022, and 0.025 $g\ cm^{-3}$, respectively. As can be seen from Fig. 9, the fluctuation of the RMSE value of the ρ_{best} by using Eq. (1) was significantly smaller and not different enough from the value of whole data compared to that of the ρ_{best} by using Eq. (2). The RMSE of the ρ_{best} by using Eq. (2) was more sensitive to the change of mass wetness from the lower to the

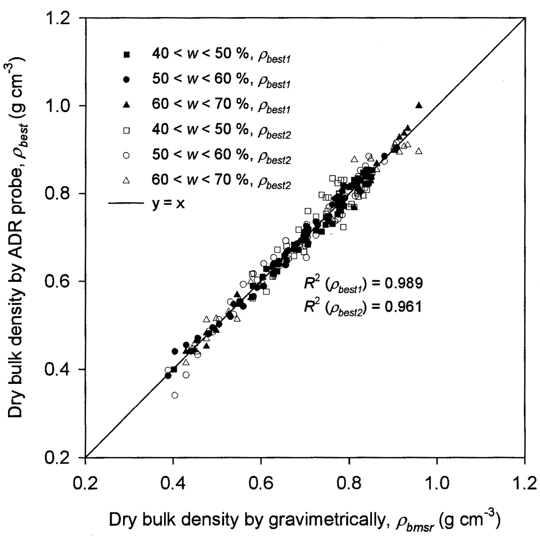

Fig. 7 Comparison between estimated and measured dry bulk density of the TUAT soil.

higher mass wetness than that by using Eq. (1). Therefore, the use of Eq. (2) in the estimation of dry bulk density became less reliable than that of Eq. (1) although the RMSE value of the ρ_{best} by using that equation was still acceptable.

Fig. 8 shows the comparison between the ρ_{best} and the ρ_{bmsr}, for the Fukaya soil. The ρ_{best} of the Fukaya soil also agreed well with the ρ_{bmsr}. The data of ρ_{best} by using Eq. (1) and ρ_{best} by using Eq. (2), which were plotted around the 1 : 1 regression line showed the R^2 value of 0.994 and 0.913, respectively. It suggested that similar to the TUAT soil the estimation of dry bulk density with wet bulk density was better than that with mass wetness. For whole data, the RMSE value of the ρ_{best} by using Eq. (1) was lower than that by using Eq. (2), such as 0.010 g cm^{-3} and 0.038 g cm^{-3}, respectively. The RMSE value within the ranges of packing dry bulk density of 0.78–0.95, 0.95–1.13, and 1.13–1.30 g cm^{-3} was fluctuated such as 0.012, 0.009, and 0.010 g cm^{-3} for the ρ_{best} by using Eq. (1), and 0.030, 0.035, and 0.048 g cm^{-3} for the ρ_{best} by using Eq. (2), respectively. The RMSE value within the ranges of mass wetness of 15–20, 20–25, and 20–30% was also fluctuated such as 0.012, 0.007 and 0.011 g cm^{-3} for the ρ_{best} by using Eq. (1), and 0.067, 0.025, and 0.033 g cm^{-3} for the ρ_{best} by using Eq. (2), respectively. As can be seen from Fig. 10,

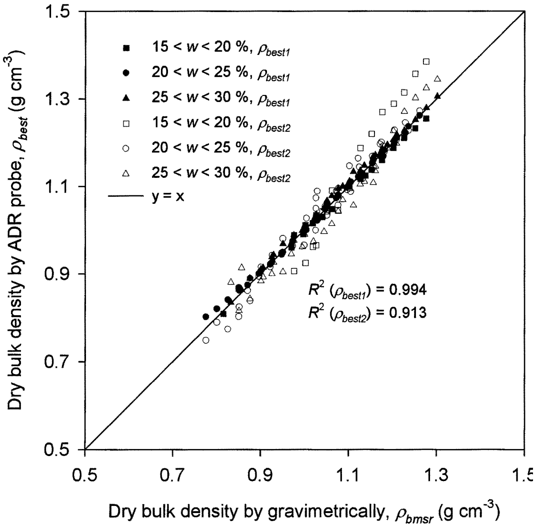

Fig. 8 Comparison between estimated and measured dry bulk density of the Fukaya soil.

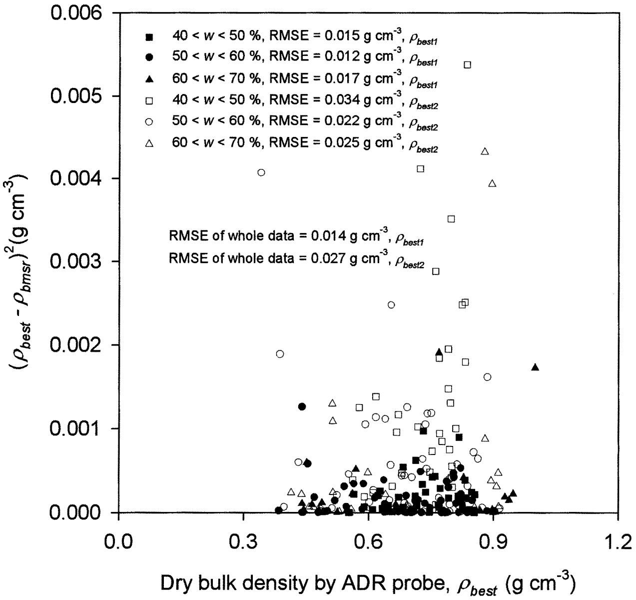

Fig. 9 Error of the estimated dry bulk density by either Eq. (1) or (2), for the TUAT soil.

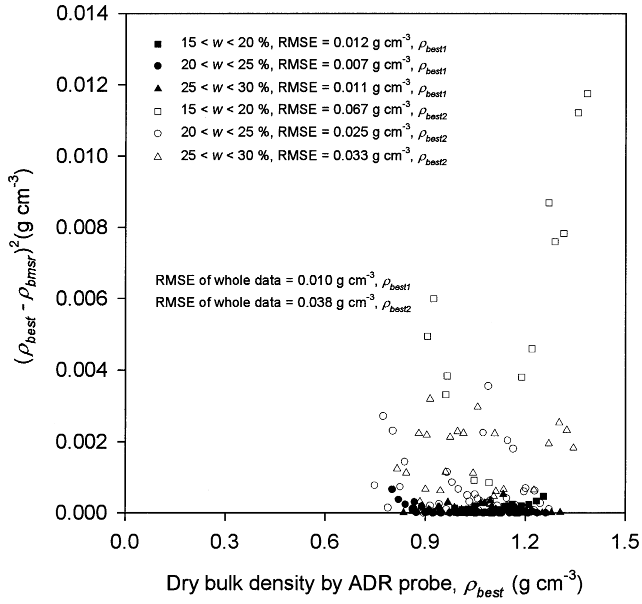

Fig. 10　Error of the estimated dry bulk density by either Eq. (1) or (2), for the Fukaya soil.

fluctuation of the RMSE value occurred in the ρ_{best} by using Eq. (2), and it was slightly in the ρ_{best} by using Eq. (1). The change of mass wetness from the lower to the higher mass wetness caused the greater RMSE value of the ρ_{best} by using Eq. (2) and had small effect on the RMSE value of the ρ_{best} by using Eq. (1). Therefore, Eq. (1) seems to give better estimation of the dry bulk density than Eq. (2) although the RMSE value resulted from the ρ_{best} by Eq. (2) was considered reasonable. Furthermore, small fluctuation of the RMSE value of the ρ_{best} of either the TUAT or the Fukaya soil suggested that the dry bulk density estimated by using the ADR data and either wet bulk density or mass wetness was independent on mass wetness of the soil. The difference in the RMSE value of the ρ_{best} between the TUAT and the Fukaya soil revealed that the type of soil had also significant effect on the accuracy of the ρ_{best}.

Incorporating the wet bulk density into the estimation of dry bulk density was more reasonable than incorporating the mass wetness. Difference in mathematical formula between Eq. (1) and (2), into which the wet bulk density or the mass wetness was substituted, may be a reason of the result above. In this calculation, since the ρ_{bmsr}, ρ_t and w value, which employ the wet and the dry soil mass of a given core volume, was carefully obtained through gravimetrically measurement, their errors was assumed to be very small and could be neglected. It was also assumed that the significant error resulted from the θ_{ADR} measurement. As Eq. (2) was mathematically formulated in a division formula, so that when the θ_{ADR} including the errors were substituted into the equation, the errors of ρ_{best} may increase since the mass wetness (w) in the Eq. (10) was always less than unity. Thus, this error may enhance with decreasing in mass wetness. On the other hand, when the θ_{ADR} data was substituted into the Eq. (1), which was known as a subtracting formula, the error of ρ_{best} shown in Eq. (9) was lower compared to when it was substituted into Eq. (2).

Derivation of Eq. (1)

$$\begin{aligned}\Delta\rho_{best1} &= |\rho_{bmsr}-\rho_{best1}| \\ &= |\rho_{bmsr}-(\rho_t-(\theta_{ADR}\times\rho_w))| \\ &= |\rho_{bmsr}-(\rho_t-((\theta_{msr}\pm\Delta\theta_{ADR})\times\rho_w))| \\ &= |\rho_{bmsr}-(\rho_t-\theta_{msr}\times\rho_w\pm\Delta\theta_{ADR}\times\rho_w)| \\ &= |\rho_{bmsr}-(\rho_{bmsr}\pm\Delta\theta_{ADR}\times\rho_w)| \\ &= |\rho_{bmsr}-\rho_{bmsr}\pm\Delta\theta_{ADR}\times\rho_w| \\ &= |\pm\Delta\theta_{ADR}\times\rho_w| \\ &= \Delta\theta_{ADR}\times\rho_w \qquad (9)\end{aligned}$$

Derivation of Eq. (2)

$$\begin{aligned}\Delta\rho_{best2} &= |\rho_{bmsr}-\rho_{best2}| \\ &= |\rho_{bmsr}-((100\times\theta_{ADR}/w)\times\rho_w)| \\ &= |\rho_{bmsr}-((100\times(\theta_{msr}\pm\Delta\theta_{ADR})/w)\times\rho_w)| \\ &= |\rho_{bmsr}-((100\times\theta_{msr}/w)\times\rho_w\pm(100\times\Delta\theta_{ADR}/w)\times\rho_w)| \\ &= |\rho_{bmsr}-(\rho_{bmsr}\pm(100\times\Delta\theta_{ADR}/w)\times\rho_w)| \\ &= |\rho_{bmsr}-\rho_{bmsr}\pm(100\times\Delta\theta_{ADR}/w)\times\rho_w| \\ &= |\pm(100\times\Delta\theta_{ADR}/w)\times\rho_w| \\ &= (100\times\Delta\theta_{ADR}/w)\times\rho_w \qquad (10)\end{aligned}$$

where, ρ_{bmsr} is the dry bulk density measured gravimetrically ; θ_{msr} is the volumetric water content measured gravimetrically ; $\Delta\rho_{best1}$ is the error of ρ_{best1} ; $\Delta\rho_{best2}$ is the error of ρ_{best2} ; $\Delta\theta_{ADR}$ is the error of the θ_{ADR} to the true θ.

In this study, since the θ_{ADR} data originally contained some extents of errors calculating the θ_{ADR} involved combination of the θ_{msr} and the $\Delta\theta_{ADR}$ ($\theta_{ADR}-\theta_{msr}=\Delta\theta_{ADR}$). This error was considered as a primarily factors affecting the accuracy of ρ_{best}, especially ρ_{best2}. For example, if the $\Delta\theta_{ADR}$ for a given soil with w ranged from 40–70% (TUAT soil) is 0.1 $cm^3 cm^{-3}$, therefore the $\Delta\rho_{best1}$ is $0.1\rho_w$, and $\Delta\rho_{best2}$ is ranged from 0.14 $(=100\times0.1/70)$ $\rho_w-0.25(=100\times0.1/40)\times\rho_w$. The phenomena indicated that the error of estimated dry bulk density with mass wetness was higher than that with wet bulk density, especially for the lower mass wetness (Fig. 9 and 10).

4. Conclusions

The output voltage using the ADR probe was not affected by neither packing dry bulk density nor mass wetness. In other word, the θ_{ADR} was independent upon these two parameters. Therefore, the ADR data can be used for estimation of dry bulk density.

The estimation of dry bulk density with wet bulk density was better than that with mass wetness. The lower accuracy of the ρ_{best} with mass wetness was affected by the division formula of calculation process.

Since the ρ_{best} was determined from the θ_{ADR}, therefore the accuracy of the θ_{ADR} was a critical factor in estimating dry bulk density.

Acknowledgement

Part of this study was supported by Grants-in-Aid for Scientific Research by Japan Society of the Promotion of Science : No. 2001–13760169.

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誘電率水分計データを用いた土壌の乾燥密度の推定

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要 旨

ADR 水分計をかく乱し詰めなおした火山灰土壌ならびに非火山灰質沖積土壌に適用し，水分計出力（volt），誘電率と体積含水率の関係を求めた。いずれの土壌も Topp（1980）の結果とは異なる誘電率–水分曲線を示した。さらに，ADR 水分計で測定した体積含水率と共に迅速，容易に測定可能な湿潤密度，含水比を用いて乾燥密度の推定を行った。いずれの土壌についても，推定した乾燥密度は，重量法で測定した値に対して，相関係数 R^2＝0.913〜0.994 で良い相関を示した。乾燥密度の推定値は，ADR による体積含水率と湿潤密度を用いたときにより良い結果を示した。

キーワード : 乾燥密度，誘電率，ADR，火山灰土壌，体積含水率

受稿年月日 : 2003 年 1 月 21 日
受理年月日 : 2003 年 9 月 19 日