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Rapid measurement of water diffusivity using a short horizontal soil column implementing a time-domain reflectometry (TDR) soil moisture sensor

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Abstract: Understanding soil hydraulic properties is essential for efficient irrigation and fertilization management in agricultural fields. Water diffusivity $D(\theta)$ is a critical parameter in hydraulic properties and is known to be directly determined using the Bruce and Klute method (conventional method). However, the conventional method presents challenges in reducing experimental time and simplifying procedures. In this study, we proposed and compared a new horizontal infiltration experiment method using time domain reflectometry (TDR) soil moisture sensor, referred to as the TDR and fixed-location observation method, with the conventional method. The results showed that the determined $D(\theta)$ values were of the same order, ranging from 0.01 to 10 cm^2 s^{-1}, across all methods, confirming that horizontal infiltration experiments using TDR soil moisture sensor are feasible. The TDR method successfully simplified the process and eliminated the cumbersome procedures of the conventional method. Moreover, while fixed-location observation method enabled quick and simple determination of $D(\theta)$, it was found that high temporal resolution was required for accurate measurement.
Key Words: water diffusivity, time domain reflectometry (TDR), dielectric constant, horizontal infiltration experiment

1. Introduction

Understanding water dynamics in unsaturated soils is important for achieving efficient irrigation and fertilization management (Ma et al., 2016). Since changes in soil moisture, such as increases due to rainfall and decreases due to drainage, affect crop growth and yield, proper permeability and water retention are vital for farmland (Miyazaki et al., 2005). Understanding the hydraulic properties of the soil is crucial for effective soil moisture management in farmland.

Water diffusivity is one of the hydraulic properties of soil to determine water dynamics in unsaturated soil (Evangelides et al., 2017) and usually described by $D(\theta)$ as a function of volumetric water content, θ. A technique for determining $D(\theta)$ known as the Bruce and Klute method (Bruce and Klute, 1956) is widely used. In this method, water is supplied from one end of a horizontally placed soil column, and $D(\theta)$ is calculated based on the θ distribution within the column after a certain period of time. However, this method is time consuming, as water infiltration into the soil column may take from several minutes to days depending on soil textures, and the process of sectioning the soil column to analyze the θ distribution is complex (Klute, 1972). Thus, it is not easy to accurately measure the θ distribution leading to undermine the precision of $D(\theta)$ estimates (Wang et al., 2004).

To overcome these difficulties, Whisler et al. (1968) proposed a fixed-location observation method that estimates $D(\theta)$ using gamma rays to measure temporal changes in θ at a specific location during horizontal infiltration. Unlike the Bruce and Klute method, this approach did not require dissecting soil columns, making it simpler (Selim et al., 1970). However, low measurement accuracy of θ with gamma rays resulted in the low accuracy of the $D(\theta)$ estimation. Furthermore, the safety concerns using radioactive materials limited its practicality for repeated experiments. Villarreal et al. (2019) subsequently used a capacitance-based soil moisture sensor (EC-5 sensor, Decagon Devices Inc., Pullman, WA, U.S.A.) to estimate $D(\theta)$ from a fixed-location of temporal changes in θ. While this method pro-

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vided high precision for $D(\theta)$ measurements at distances greater than 15 cm from the water inlet, significant errors occurred at 10 cm. They attributed this to rapid changes in θ near the water inlet and suggested placing sensors at least 15 cm away. Wang et al. (2004) proposed a non-destructive method to estimate $D(\theta)$ by tracking wetting front location and cumulative infiltration over time. This method worked effectively for wetting front location of 10 cm or greater but showed reduced precision for distances under 8 cm. To shorten measurement time, a method that can estimate $D(\theta)$ based on θ changes near the water inlet is desirable, but both Wang et al. (2004) and Villarreal et al. (2019) noted the difficulty of achieving this. On the other hand, Noborio and Sato (2022) used simulations to show that θ could be measured at a distance of 5 cm from the water inlet to determine $D(\theta)$ using a modified Bruce and Klute method. Since the infiltration distance is theoretically proportional to the square root of time, reducing the measurement distance from 10 cm to 5 cm is expected to decrease the required time by $1/4$. This substantial reduction in measurement time illustrates one of the key advantages of the proposed method, particularly when rapid measurement is essential. While this method allows rapid and non-destructive measurement of θ, it remains untested in practical experiments. In addition, previous studies have not employed time-domain reflectometry (TDR) soil moisture sensors in horizontal infiltration experiments, and it remain unclear whether such an application is even feasible.

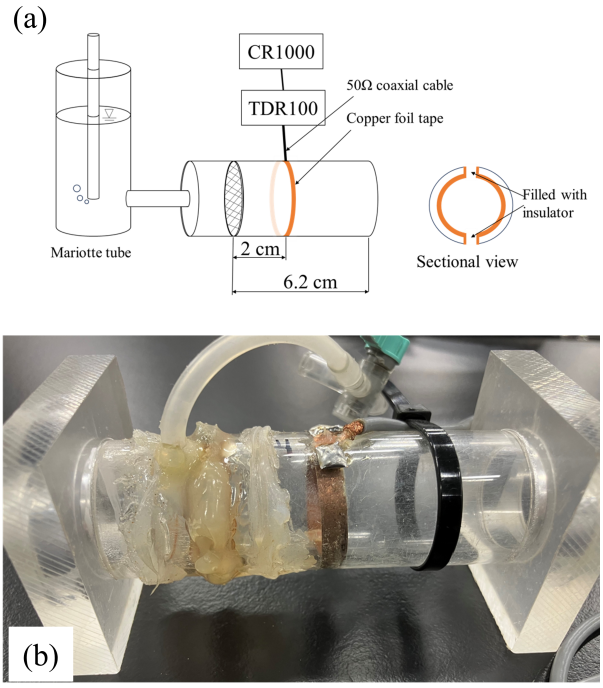


Fig. 1 Experimental apparatus for fixed-location observation method (a: diagram, b: photograph).

This study proposed a rapid method for determining $D(\theta)$ based on the Bruce and Klute theory, which Noborio and Sato (2022) proposed, by measuring θ with column-implementing TDR. Additionally, a non-destructive Bruce and Klute method was conducted to evaluate its effectiveness implemented with TDR soil moisture sensors.

2. Materials and Method

The experiment for the newly proposed method was conducted in a laboratory with a room temperature of approximately 24 °C at Ikuta Campus, Meiji University in Kawasaki, Japan. Toyoura sand was utilized for the experiment. We also conducted two additional conventional methods to evaluate the new method: the Bruce and Klute method (Bruce and Klute, 1956) and the Bruce and Klute method with implementing TDR. Following the calculation procedure that Katsuta et al. (2016) detailed, $D(\theta)$ was determined by the Bruce and Klute method accordingly. Each method was conducted in triplicates.

2.1 Fixed-location observation method (proposed method)

A rapid horizontal infiltration experiment was conducted following the method proposed by Noborio and Sato (2022). The newly proposed method used a short acrylic cylindrical column with an inner diameter of 2.4 cm and a length of 6.2 cm was prepared. This shorter column length was employed to facilitate easier packing and reduce the overall experimental time. The use of a shorter column also addressed practical challenges associated with conducting experiments, such as improving reproducibility and enabling more efficient repetition of trials. Two strips of copper tape, each 3.8 cm long and 0.5 cm wide, were affixed opposite each other to the inner wall at a location 2.0 cm from the water inlet (Fig. 1). One end of the copper tape was soldered to a 50 Ω coaxial cable, forming a two-wire TDR soil moisture sensor. The 50 Ω coaxial cable was connected to a TDR unit (TDR100, Campbell Scientific Inc., Logan, UT, U.S.A), and TDR waveforms were recorded every 2 s, at the minimum measurement interval of TDR100 (Campbell Scientific, 2012), using a datalogger (CR1000, Campbell Scientific Inc., Logan, UT, U.S.A.).

The column was filled with air-dried Toyoura sand at a dry bulk density of 1.62 ± 0.01 Mg m^{-3}. After horizontally positioning the soil column, one end was connected to a Mariotte bottle filled with tap water equilibrated to room temperature. The lower end of the Mariotte bottle's tubing was adjusted to align with the center of the soil column. Air was removed from the tubing between the Mariotte bottle and the entrance of the soil column by pulling

with a syringe to initiate infiltration. The moment when the tap water began entering the soil was defined as time $t = 0$ s, defined as the infiltration solution began entering the soil. The water supply was stopped immediately when the infiltration front reached the 5 cm mark from the water inlet. The infiltration time at that moment was 24 s.

From obtained TDR waveforms, the dielectric constant ε, was calculated using Eq. (1).

$$\varepsilon = \left(\frac{L_a}{L}\right)^2 \tag{1}$$

where L_a represents the apparent length of a copper tape strip (m), and L denotes the actual length of the copper tape strip (m).

Since the copper tape was affixed to the inner wall of the acrylic column, the dielectric constant of the acrylic must be accounted for when determining the soil's dielectric constant (Miyamoto and Chikushi, 2006). Therefore, the true dielectric constant of the soils, ε', was calculated using Eq. (2).

$$\varepsilon = a\varepsilon' + b\varepsilon_{ac} \tag{2}$$

where ε is the apparent dielectric constant calculated using Eq. (1), ε_{ac} is the dielectric constant of the acrylic material, and a and b are experimental constants.

To determine a and $b\varepsilon_{ac}$, the TDR waveforms, in which the acrylic column was filled with air and water, were respectively acquired to calculate their ε. The true dielectric constants of air and water were assumed to be 1 and 80, respectively (Noborio, 2003). By substituting these values into Eq. (2), a and $b\varepsilon_{ac}$ were determined. As a and $b\varepsilon_{ac}$ are specific to each probe, these values were determined for each probe individually. Using Eq. (2) with the a and $b\varepsilon_{ac}$ values just determined, the ε' value was calculated, and the volumetric water content, θ ($m^3\ m^{-3}$), was then determined using Eq. (3) (Topp et al., 1980).

$$\begin{aligned}\theta = &-5.3\cdot10^{-2} + 2.92\cdot10^{-2}\varepsilon' \\ &- 5.5\cdot10^{-4}\varepsilon'^2 + 4.3\cdot10^{-6}\varepsilon'^3\end{aligned} \tag{3}$$

The distribution of moisture, originally represented by time t (s) and θ, was converted to the Boltzmann variable λ ($cm\ s^{-0.5}$) and θ, allowing the calculation of $D(\theta)$ using Eq. (4) (Noborio and Sato, 2022).

$$D(\theta) = -\frac{1}{2}\left.\frac{d\lambda}{d\theta}\right|_{\lambda_t}\int_{\theta_{t=0}}^{\theta_t}\lambda d\theta \tag{4}$$

where λ_t represents the Boltzmann variable at t ($\lambda = xt^{-0.5}$), x is the distance from the water inlet to the TDR soil moisture sensor (= 2.0 cm), θ_t is the volumetric water content ($m^3\ m^{-3}$) at t, and $\theta_{t=0}$ is the initial volumetric water content ($m^3\ m^{-3}$).

2.2 The Bruce and Klute method (conventional method)

A horizontal infiltration experiment was conducted following Bruce and Klute (1956). A soil column was made by connecting 40 acrylic rings (inner diameter was 2.4 cm with 1.0 cm long) using a cellophane tape. The column was filled with air-dried Toyoura sand at a dry bulk density of 1.62 ± 0.01 Mg m^{-3}. The remainder of the procedure to initiate infiltration was mentioned above in Section 2.1. When the infiltration front reached a distance of 35–40 cm to obtain sufficient measurement points for water content distribution, the water supply was stopped. At that moment, the infiltration time was 780 s. Immediately afterward, the soil column was vertically positioned with the water intake side downward and sectioned into 1 cm segments starting from the dry end. Each segment was transferred to the crucible, and its mass was measured. Soil samples in each segment were then oven-dried at 110 °C for more than 24 hours to determine the volumetric water content θ. The spatial moisture distribution curve, which shows the relationship between θ and the distance y (cm) from the water inlet, was used to calculate $D(\theta)$ using Eq. (5) (Bruce and Klute, 1956):

$$D(\theta) = -\frac{1}{2t_c}\left.\frac{dy}{d\theta}\right|_{\theta_y}\int_{\theta_i}^{\theta_y} y d\theta \tag{5}$$

where θ_y represents the volumetric water content ($m^3\ m^{-3}$) at y from the water inlet, θ_i denotes the initial volumetric water content ($m^3\ m^{-3}$), and t_c is the infiltration time (s).

2.3 The Bruce and Klute method using TDR (TDR method)

The conventional method to measure moisture distribution by dissecting the column was replaced with a non-destructive method using TDR soil moisture sensor. An acrylic cylindrical column with an inner diameter of 2.4 cm and a length of 42 cm was used for housing copper tape strips, measuring 3.8 cm in length and 0.5 cm in width, which were attached in pairs opposite each other to the inner wall at distances of 4, 8, 12, 16, 20, and 24 cm from the water inlet (Fig. 2). One end of each copper tape strip was soldered to a 50 Ω coaxial cable, forming a two-wire TDR soil moisture sensor. The coaxial cables were connecting to TDR100 via a multiplexer (SDMX50, Campbell Scientific Inc., Logan, UT, U.S.A.). The column was filled with air-dried Toyoura sand at a dry bulk density of 1.62 ± 0.01 Mg m^{-3}. The remainder of the procedure to initiate infiltration was mentioned above in Section 2.1. The TDR

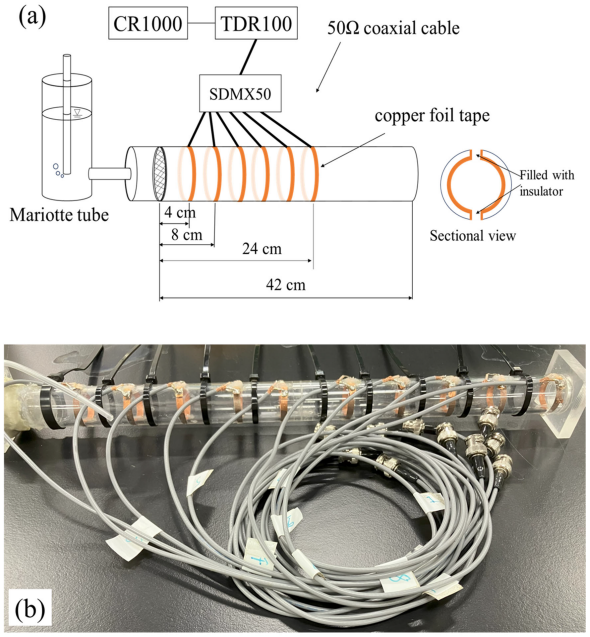


Fig. 2 Experimental apparatus for TDR method (a: diagram, b: photograph).

waveform data were recorded every 30 s using CR1000, since measurements at 2 s intervals resulted in unstable waveforms. The experiment was terminated by stopping the water supply after the infiltration front reached 35 cm from the water inlet. At that moment, the infiltration time was 780 s.

To determine $D(\theta)$, the spatial moisture distributions at $t_c = 300$, 360, 420, and 780 s — selected based on the passage times of the infiltration front through the 20–24 cm location and the infiltration time used in the conventional method — were normalized using the Boltzmann variable $\lambda = yt_c^{-0.5}$. Using moisture distribution curves representing the relationship between λ and θ, $D(\theta)$ was calculated using Eq. (6) (Bruce and Klute, 1956).

$$D(\theta) = -\frac{1}{2}\frac{d\lambda}{d\theta}\bigg|_{\theta_y}\int_{\theta_i}^{\theta_y}\lambda d\theta \qquad (6)$$

3. Results and Discussion

The $D(\theta)$ values determined by different methods are showed in Fig. 3. In this figure, the x-axis represents θ, and the y-axis represents $D(\theta)$. In previous studies, the $D(\theta)$ was evaluated using methods based on measurement principles different from those employed in this study, and discrepancies in the $D(\theta)$ values obtained for the same soil have been reported (Meyer and Warrick, 1990; Ma et al., 2016; Villarreal et al., 2019). A similar trend was observed in the present study, thereby confirming the feasibility of evaluating water diffusivity using the proposed method. Since the order of $D(\theta)$ was consistent across all methods, it was confirmed that horizontal infiltration experiments using TDR soil moisture sensor are feasible. In the fixed-location observation method, the infiltration time was 24 s, which was significantly shorter, less than 1/30 times, compared to the infiltration time of 780 s in both the conventional and TDR methods.

3.1 Conventional method vs TDR method

When comparing $D(\theta)$ determined by the conventional and the TDR methods, good agreement was observed for $\theta \leqq 0.3$ m^3 m^{-3}. However, for $\theta > 0.3$ m^3 m^{-3}, the conventional method yielded larger $D(\theta)$ than the TDR method (Fig. 3). Tyner and Brown (2004) and Ma et al. (2016) reported that even minor errors in the moisture gradient ($d\lambda/d\theta$) resulted in significant errors in $D(\theta)$ especially in higher water contents. Villarreal et al. (2019) reported similar findings. Thus, observed differences in $D(\theta)$ values across methods are likely attributable to variations in the moisture distribution data used for calculation.

Fig. 4 shows the relationship between λ and θ obtained by each method. In this figure, the x-axis represents λ, while the y-axis represents θ. Since the relationship between $D(\theta)$ and θ is intrinsic to a given soil, the relationship between λ and θ should be independent of the measurement method and thus remain consistent (Noborio and Sato, 2022). In this context, t in λ is treated as a constant; thereby, only the spatial coordinate varies. In the conventional method, for $0.3 < \theta < 0.45$ m^3 m^{-3}, θ exhibited lower values in the range $0 < \lambda < 1$ cm s$^{-0.5}$ compared to other methods. The conventional method required the soil column to be sectioned after the infiltration experiment. The column was vertically positioned with the water intake side downward and cut from the dry end using a knife during this process. This process made water within the soil move downward, leading to moisture redistribution in the column, with some water even flowing out from the column. Consequently, the conventional method likely underestimated θ for $\theta > 0.3$ m^3 m^{-3} compared to its actual value immediately after infiltration ended. In contrast, the TDR method allows non-destructive measurement of moisture distribution without disassembling the column, thereby preventing moisture redistribution encountered in the conventional method. By using the TDR method, errors in θ measurements resulted from moisture redistribution were minimized, resulting in improved accuracy in determining $D(\theta)$.

3.2 TDR method vs Fixed-location observation method

In the fixed-location observation method, the measurement interval was short relative to the infiltration rate, resulting in a limited number of data points captured within

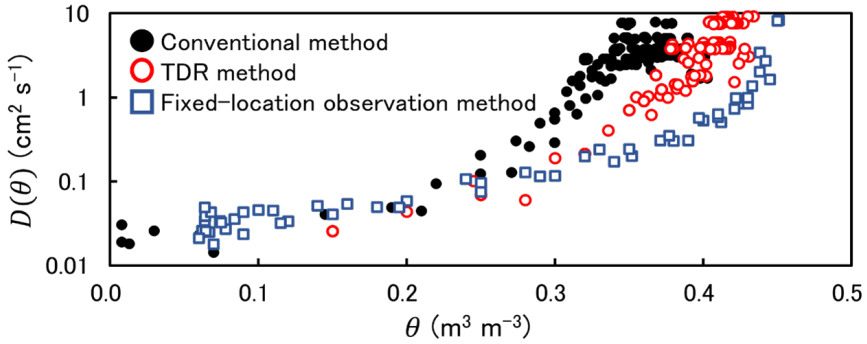


Fig. 3 Water diffusivity ($D(\theta)$, cm^2 s^{-1}) at different volumetric water content (θ, m^3 m^{-3}), with data collected from three repetitions (black circle: Conventional method, open red circle: TDR method, open blue square: Fixed-location observation method).

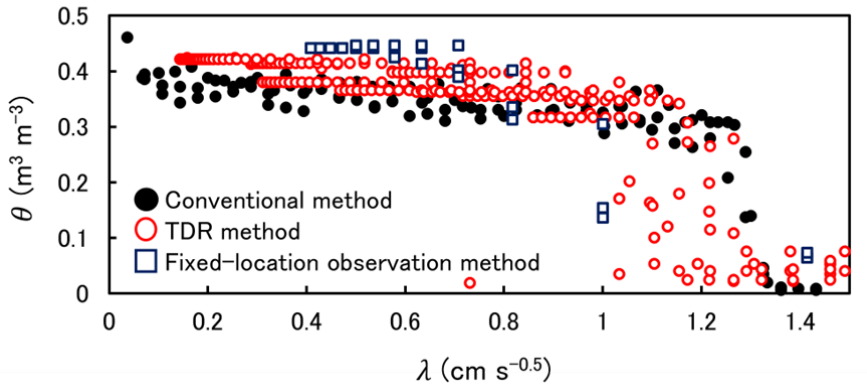


Fig. 4 Volumetric water content (θ, m^3 m^{-3}) versus Boltzmann variable (λ, cm s$^{-0.5}$) for each method, with data collected from three repetitions (black circle: Conventional method, open red circle: TDR method, open blue square: Fixed-location observation method).

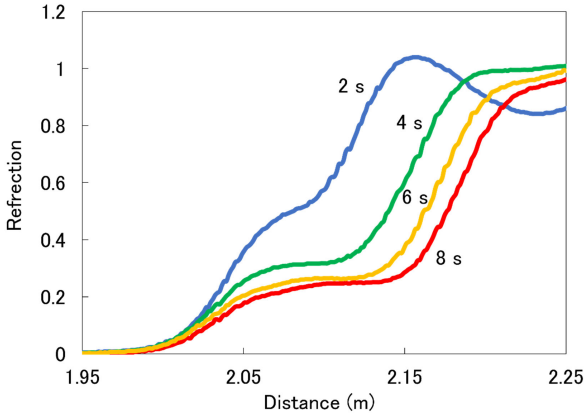


Fig. 5 TDR waveform data obtained by Fixed-location observation method at 2 s intervals from 2 s to 8 s. After 8 s, TDR waveform did not change.

the partially saturated zone. The TDR waveform data obtained from the fixed-location observation method are shown in Fig. 5. Fig. 5 shows apparent electrical distance on the x-axis and reflection coefficient on the y-axis. The interpretation of TDR waveforms is described in detail by He et al. (2021), therefore, readers are referred to their work for further information. The waveform clearly changed with increasing soil water content. Although the variations in soil water content were successfully observed, it was evident that 2 s measurement interval was not precise enough to follow sudden changes in moisture content accurately. The main issue here is the spatial extent of the region between the 2 s and 4 s waveforms (blue and green waveform, respectively). In TDR measurements, increasing the water content slows the signal velocity, resulting in a longer apparent probe length. Therefore, as the wetting front advances, the reflection point in the waveform shifts to the right. Ideally, the waveform shift should gradually follow an increase in the water content. However, in this case, the difference between the 2 s and 4 s waveforms was large and abrupt, indicating that the change in water content occurred too rapidly to be captured accurately in this time interval.

When comparing $D(\theta)$ determined by the TDR and the fixed-location observation methods, good agreement was observed for $\theta \leqq 0.35$ m^3 m^{-3}. However, for $\theta > 0.35$ m^3 m^{-3}, the TDR method yielded larger $D(\theta)$ than the fixed-location observation method (Fig. 3). A similar phenomenon occurred in the high moisture range in the conventional method as described in Section 3.1. Since λ is

a variable that allows the collapse of spatial and temporal data into a single curve (Boltzmann, 1894), the relationship between θ and λ for the same soil should theoretically remain constant regardless of the measurement method (Noborio and Sato, 2022). However, as shown in Fig. 4, large change in θ occurred at $0.8 < \lambda < 1$ cm s$^{-0.5}$ in the fixed-location observation method, whereas these occurred at $1 < \lambda < 1.2$ cm s$^{-0.5}$ in the TDR method. In the fixed-location observation method, λ is defined with distance as a constant and time as a variable. Therefore, the value of λ depends on the square root of time, making it highly sensitive to even slight time measurement errors. In this study, measurements were taken at the minimum sampling interval of 2 s, as specified by the equipment, i.e., TDR100 (Campbell Scientific, 2012). However, this interval was likely insufficient for highly permeable sand to capture the rapid changes in θ near the water inlet. Increasing the distance of the observation point from the water inlet may help improve the issue of limited temporal resolution. However, as the distance from the water inlet increases, the infiltration front moves beyond the observation point under unsaturated conditions, after which the waveform exhibits minimal change. Consequently, it becomes difficult to obtain data related to near-saturated water content; thus, placing the sensor farther from the water inlet may lead to reduce measurement accuracy. Therefore, to achieve a more accurate determination of $D(\theta)$ using the fixed-location observation method, it is necessary to improve the temporal resolution of soil moisture measurements.

4. Conclusion

This research valuated two newly proposed methods for determining $D(\theta)$ using time domain reflectometry (TDR): the TDR and fixed-location observation methods, by comparing them with the conventional Bruce and Klute method (conventional method). Using the fixed-location observation method, $D(\theta)$ comparable to those obtained by the conventional method were confirmed. In addition, this method allowed simple and highly reproducible experimental procedures, and significantly reduced measurement time compared to the conventional method. It also enables rapid and straightforward estimation of θ. However, the low temporal resolution prevented precise tracking of θ variations, reducing the accuracy of λ measurements and leading to an underestimation of $D(\theta)$. Thus, for rapid estimation of $D(\theta)$ via the fixed-location observation method, θ must be measured at a higher temporal resolution.

The conventional method required extensive time and complex procedures and faced the challenge of moisture redistribution when sectioning the soil column, leading to underestimating θ. In contrast to the conventional method, the TDR method prevented moisture redistribution and estimated θ by non-destructive and simpler procedures. Therefore, among the methods evaluated in this study for estimating $D(\theta)$, the TDR method is the most recommended. In both the conventional and TDR methods, shortening the water supply time may result in an insufficient number of measurement points within the unsaturated zone, leading to reduced accuracy in the estimation of $D(\theta)$. Furthermore, in the conventional method, a shorter water supply time often leaves a larger portion of the column in a dry state, making it more difficult to recover soil samples during disassembly and potentially compromising the reproducibility and reliability of the experiment. Therefore, when calculating $D(\theta)$ based on the spatial distribution of water content, it is essential to ensure a sufficient infiltration distance over time. Although the fixed-location observation method was limited by the low temporal resolution of the sensor in this study, it demonstrated high potential in terms of simplicity, reproducibility, and reduced experimental time. If sensors with higher temporal resolution are employed, this method may offer a more practical alternative to the TDR method and enable more precise estimation of $D(\theta)$ in a shorter time.

In this study, the infiltration time for the conventional method was set to 780 s, corresponding to the wetting front reached at 35 cm from the water inlet. For the TDR method, the infiltration time was determined when the wetting front reached a point between midpoint of the column (20 cm) and a sensor location just beyond the midpoint (24 cm), in addition to the 780 s used in the conventional method. In the fixed-location observation method, the infiltration time was set to 24 s when the wetting front reached the 5 cm sensor position.

While horizontal infiltration experiments using TDR soil moisture sensors were shown to be feasible, this study used only sand as the test soil, requiring further evaluation of the proposed method's applicability to other soil types.

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要　　旨

農地において効率的な灌漑や施肥管理を行うためには土壌の水理特性の把握が重要である．水分拡散係数 $D(\theta)$ は水理特性の重要なパラメータであり，Bruce and Klute 法（従来法）で直接決定可能であることが広く知られているが，従来法では実験時間の短縮や作業の簡略化が課題として残っている．本研究では time domain reflectometry（TDR）土壌水分計を用いた定点観測法を提案し，従来法および従来法に TDR 水分計を付加した TDR 法と比較した．定点観測法では迅速かつ簡易に $D(\theta)$ が決定可能であったが，測定に高い時間分解能が必要であることが明らかになった．TDR 法では従来法の課題であった煩雑な作業を解消でき，簡易に $D(\theta)$ を決定可能であった．すべての方法で決定した $D(\theta)$ は 0.01 から 10 cm^2 s^{-1} の間にあり，同様のオーダーであったため，TDR 土壌水分計を用いた水平浸潤実験は有用であることが明らかになった．

キーワード：水分拡散係数，time domain reflectometry（TDR），比誘電率，水平浸潤実験