J. Jpn. Soc. Soil Phys., March 2012, Vol. 120, 55-60

A simple and low cost method for measuring gas diffusivity and air permeability over a single soil cylinder

Purwoko Hari KUNCORO[1] and Kiyoshi KOGA[2]

Abstract : A low cost unified system for relative gas diffusivity (D_p/D_0) and air permeability (k_a) measurements has been developed. Instead of the conventional sliding-mechanism, plastic films' shutter has been proposed for the D_p/D_0 measurement. While for the k_a measurement, a method has been introduced by utilizing the principle of Mariotte's bottle and manometers instead of much costing air pump, mass flow meter, and pressure sensor/gauge. The measured D_p/D_0 and k_a of Toyoura sand were in a good agreement with those obtained in the literature, and the proposed method enabled to lower the apparatus cost up to 40 % of the common method cost.

Key Words : gas diffusivity, air permeability, measurement

1. Introduction

Diffusion that is driven by concentration gradient and convection that is driven by pressure gradient are the two main process of gaseous-transport in the soil (Hillel, 1998). Information on those properties is of importance for describing soil aeration (Taylor, 1949 ; Glinski and Stepniewski, 1985) and for assessing the greenhouse gases emission (Ball et al., 1997 ; Smith et al., 2003) as well as volatile gas movement in the soil (Jury et al., 1990 ; Petersen et al., 1996). In addition, such information is also valuable to be used as a proxy for soil hydraulic conductivity properties (Poulsen et al., 2001 ; Chief et al., 2006).

The parameter for gas diffusion is gas diffusivity, which is commonly expressed as a relative diffusivity D_p/D_0 in which D_p is the gas diffusivity in soil [m^2 s^{-1}] and D_0 is the gas diffusivity in free air [m^2 s^{-1}]. For this D_p/D_0 measurement, a sliding-mechanism has been widely employed for insulating the initial concentration of the tracer gas used in the diffusion chamber (Currie, 1960 ; Osozawa, 1987 ; Rolston and Moldrup, 2002 ; Resurreccion et al., 2008). However, such mechanism takes a budgeting allocation for the construction and might require certain sealing-effort prior to the measurement.

On the other hand, modern tools like air pump, mass flow meter, and pressure sensor/gauge have been commonly used to measure the air permeability k_a [μm^2] (Chief et al., 2006 ; Hamamoto et al., 2009a). Certainly, such tools must be convenient in handling and eligible for precise data measurement. However, they might be remained much costing among us who had severe limitation on the research-budgeting circumstance.

Accordingly, this study is aimed to propose a low cost method for measuring D_p/D_0 and k_a over a single soil cylinder.

2. Development of the measurement method

2. 1 Soil specimen preparation

Toyoura sand with 0.42-0.02 mm in particle size fractions (Table 1) is repacked into a 471 cm^3 cylinder with 10 cm i.d. and 6 cm length and is used for D_p/D_0 and k_a measurements undergoing air-dry and variably-saturated conditions. For the measurement at air-dry condition, the Toyoura sand is simply air-dried prior to the repacking. While for the measurement at variably-saturated conditions, repacked air-dried Toyoura sand is first, water saturated, and then be drained at −50, −75, and −125 cm soil water matric potentials using hanging water column method. The Toyoura sand is not repacked undergoing wet condition since such handling may cause a change in its structure as the Toyoura sand mainly consists of the elongated soil particles (Hamamoto et al., 2009b).

Table 1 Physical properties of the used Toyoura sand at air-dry condition.

Bulk density (g cm^{-3})	1.58
Particle density (g cm^{-3})	2.64
Gravimetric water content (%)	almost zero
Total porosity (m^3 m^{-3})	0.40

[1]Graduate School of Agriculture, Iwate University, 3-18-8 Ueda, Morioka 020-8550, Japan. Corresponding author : Purwoko Hari Kuncoro
[2]Faculty of Agriculture, Iwate University, 3-18-8 Ueda, Morioka 020-8550, Japan.
2011 年 11 月 9 日受稿，2011 年 12 月 28 日受理
土壌の物理性 120 号，55-60（2012）

2. 2 Gas diffusivity measurement

D_p/D_0 (and also for the later k_a) measurement is conducted at 20 ℃ with three of replication for each of expected soil air content ε [m^3 m^{-3}]. As suggested by El-Farhan et al. (1996), the size of diffusion chamber is designed to be almost similar to that of the soil cylinder, which is 463 cm^3 in net volume with 11 cm i.d. and 5 cm length, in order to minimize errors which may be incurred by non-mixing of the gas in the chamber. On the other hand, O-ring is used to seal the chamber and no-leakage condition is confirmed by immersing the apparatus into water.

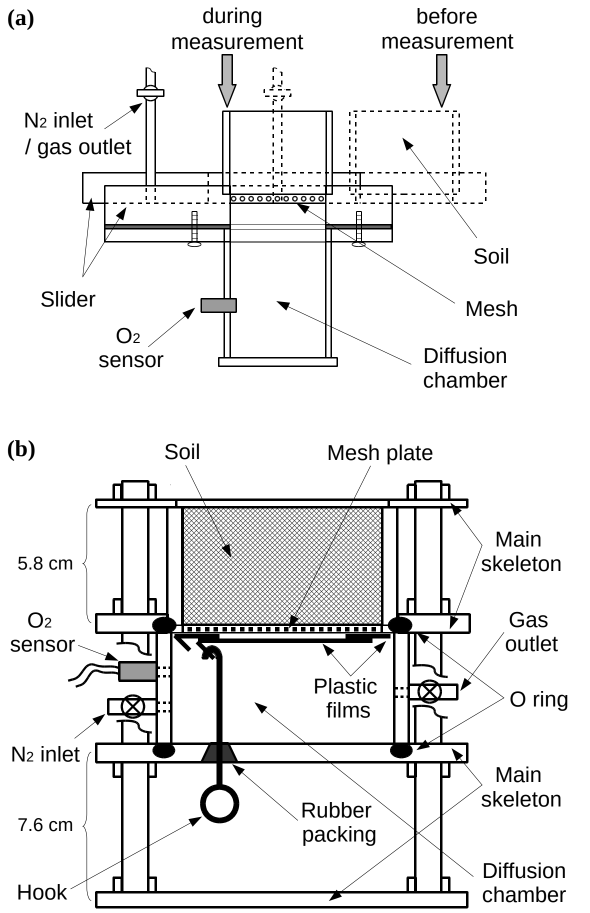

Fig. 1 Conventional sliding-mechanism (after Osozawa, 1987) (a) and the proposed diffusionmeter apparatus (b).

Instead of the conventional sliding-mechanism (Fig. 1a), a set of plastic films that is equipped with a hook is used as a shutter (Fig. 1b). These 0.2 mm thick plastic films of polypropylene shape into a circle and a ring as shown in Fig. 3b. The end part of outer surface of this circle-shaped plastic film is first, attached to the inner-surface of the ring-shaped plastic film using vacuum grease. And then, the outer-surface of this ring-shaped plastic film is attached to a 0.3 cm thick stainless steel mesh plate (Fig. 3a) using the same grease prior to the measurement. Such a vacuum grease usage is preferable since it can provide a sufficient sealing-function prior to the measurement but yet enables the plastic films to be easily peeled off for the measurement.

Fig. 2 Photo of the diffusionmeter apparatus.

Since O_2 will be used as a tracer gas, N_2 is preliminary injected into the diffusion chamber until the O_2 concentration reaches almost zero. The measurement begins when the circle-shaped plastic film, which is subsequently followed by ring-shaped plastic film, is pulled down.

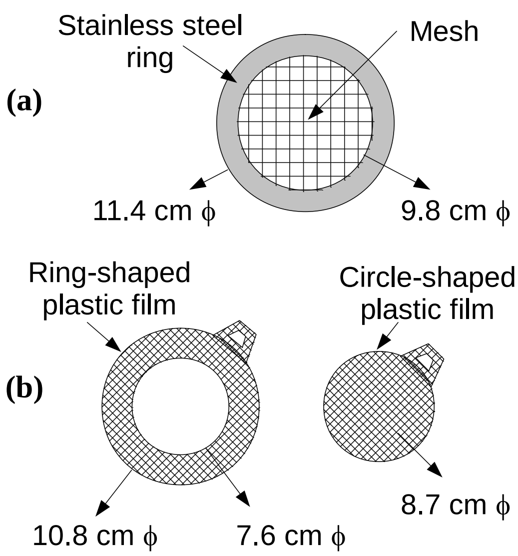

Fig. 3 Mesh plate (a) and Plastic films' shutter (b).

For the sake of its simplicity, the shutter may be designed into a single circle-shaped plastic film only, which is about 10.8 cm in diameter. However, such large diameter may cause a certain part of this plastic film to be sometimes remained attached to the mesh plate as the maximal hook displacement inside the chamber is only about 4 cm so that the pulling-force may be insufficiently transferred to this furthest point. Hence, the process of air mixing in the chamber may be constrained, particularly over area beneath this diagonally remained plastic film.

Thus, the shutter that consists of a ring and a smaller circle of plastic films is preferable in this study. This smaller diameter of 8.7 cm makes the circle-shaped plastic film can be easily peeled off previously. Therefore, air mixing in the chamber can be surely started even if the ring-shaped plastic film remained diagonally across the chamber.

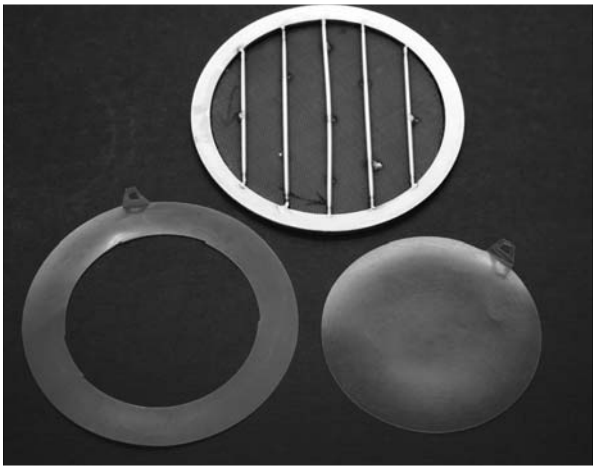

Fig. 4 Photo of the mesh plate and plastic films' shutter.

Along the measurement, concentration of O_2 in the chamber is measured by a galvanic O_2 sensor (KE-12, Yuasa Co.) and the output is recorded by a data logger. Then, the value of D_p can be calculated from the slope (linear regressed) of the plot of relative O_2 concentration C_r vs. time t as described by Currie (1960) and Rolston and Moldrup (2002). The relative O_2 concentration C_r is defined as

$$C_r = \frac{C_t - C_a}{C_0 - C_a} \qquad (1)$$

in which C_0 is the initial O_2 concentration in the chamber (%), C_t is O_2 concentration in the chamber at time t (%), and C_a is O_2 concentration in free air (%).

Finally, by taking D_0 as 2.0 x 10^{-5} m^2 s^{-1} at 20℃ (Currie, 1960), the value of D_p/D_0 can be determined.

2. 3 Air permeability measurement

After the D_p/D_0 measurement, the same chamber and soil cylinder are used for k_a measurement using Mariotte's bottle and manometers. Manometer A is attached to the N_2 inlet port of the chamber and manometer B is connected to the air in the Mariotte's bottle, whereas the gas outlet port is connected to the pipe of the Mariotte's bottle (Fig. 5). Meanwhile, the plastic film shutters are remained peeled off from the mesh plate.

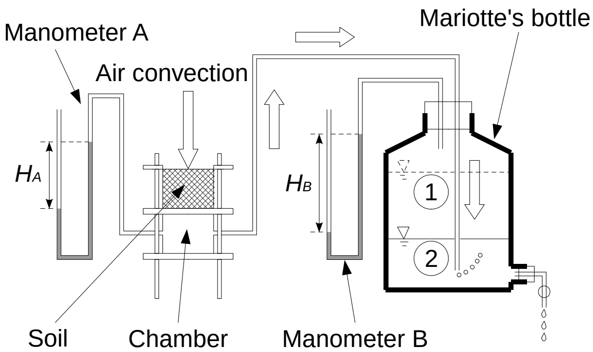

Fig. 5 Air permeameter apparatus.

Fig. 6 Photo of tools set-up for k_a measurement.

As the water is open-released from the outlet of the Mariotte's bottle (26 liter in capacity), the atmospheric air is pulled into the system through the soil specimen, and the occurred pressure gradient across the soil specimen becomes constant because the level of the water outlet has been fixed along the measurement. The expected pressure gradient for a certain measurement, however, can be set to some extent by simply adjusting the level of this water outlet.

Soon after the manometer A became stable, the k_a measurement can be conducted by recording the change of air volume in the Mariotte's bottle and the reading of manometer A and manometer B for a certain time interval (e.g. 2 minutes) within a set of replication (e.g. 6 times). Average of the calculated k_a from those measurements is then taken as the final k_a value.

Fig. 7 Photo of the used Mariotte's bottle.

Principally, k_a will be calculated from the volume flux of the permeated air, and the volume of the permeated air itself is determined from the water level in the Mariotte's bottle. Hence, a certain calibration is preliminary required to convert the measured water level into air volume in the Mariotte's bottle.

Since air volume changes with absolute air pressure, the value of k_a can be determined through the following procedure. Suppose suffix 1 and 2 denote the start and the end of the measurement, respectively, while atm is absolute atmospheric pressure [Pa], ρ_w is water density [kg m^{-3}], g is gravitational acceleration [m s^{-2}], and H is the difference in water level in manometer [m]. Hence, absolute air pressure in the chamber P_A [Pa] can be expressed as

$$P_A = atm - \rho_w g H_A \tag{2}$$

while, absolute air pressure in the Mariotte's bottle P_B [Pa] will be

$$P_B = atm - \rho_w g H_B \tag{3}$$

By carrying ideal gas equation, mole number of the permeated air through soil n [mole] can be written as

$$n = (P_{B2}V_2 - P_{B1}V_1)/RT \tag{4}$$

in which V is the volume of air in the Mariotte's bottle [m^3], R is gas constant [J K^{-1} mol^{-1}], and T is absolute temperature [K].

As absolute pressure of the permeated air at the center of the specimen P_c [Pa] is

$$P_c = (atm + P_A)/2 \tag{5}$$

according to the Boyle's law, the volume of the permeated air at the center of the specimen ΔV_c [m^3] during the measurement can be calculated as

$$\Delta V_c = \frac{n}{P_c} RT = 2\left(\frac{P_{B2}V_2 - P_{B1}V_1}{atm + P_A}\right) \tag{6}$$

Hence, volume flux of air q_a [m s^{-1}] during measuring time Δ_t [s] will be

$$q_a = \frac{\Delta V_c}{A \Delta t} \tag{7}$$

in which A is the cross-sectional area of the specimen [m^2].

Finally, k_a [μm^2] can be calculated as

$$k_a = q_a \eta_a \frac{L}{\rho_w g H_A} \tag{8}$$

in which L is the length of the specimen [m] and η_a is the air dynamic viscosity [Pa s].

3. Results and discussion

Although measured D_p/D_0 and k_a, particularly at wet conditions, tended to be slightly lower than those obtained in the literature (Hamamoto et al., 2009b), there was a fairly good agreement between them (Fig. 8). Those slightly lower values, particularly in k_a, were possibly attributed to the lower ratio of fringes between sand particle and wall of the soil cylinder to the soil cross-sectional area, namely the inner diameter of the soil cylinder in this study was 10 cm, whereas it was 5 cm in the literature. Accordingly, the developed method was considered to be acceptable for D_p/D_0 and k_a measurements.

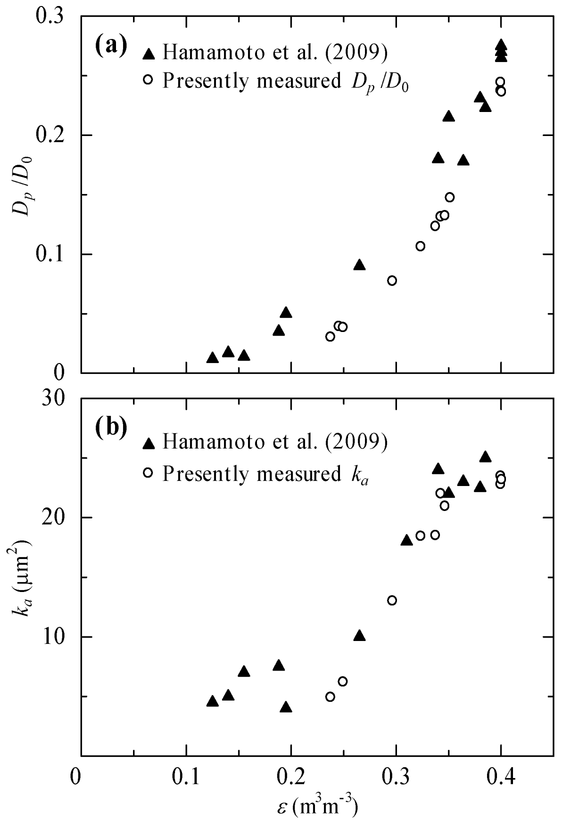

Fig. 8 Measured D_p/D_0 (a) and measured k_a (b) at various air content ε.

The developed method enabled to lower the cost up to 40 % of the common method cost as it omitted the most cost of slider compartment, mass flow meter, pressure sensor, and air pump (Table 2). The slider compartment much costs due to the required perfectly-flatten surfaces for its well sliding-work and sealing-effort.

In addition, most devices that were used in this developed method are considered to have a favorable durableness as they are reusable or possessing long-life services. For instance, lack in water inside the manometers and Mariotte's bottle due to the evaporation and measurement usage, respectively, may be simply overcome by adding water. While, the plastic film is customary reusable as long as it is neither being folded nor torn up.

4. Conclusion

The proposed plastic films' shutter for D_p/D_0 measurement and the usage of Mariotte's bottle with manometers for k_a measurement are sufficient for a unified D_p/D_0 and k_a measurements. As the developed method enables to lower the apparatus cost significantly, further study on D_p/D_0 and k_a (e.g. effects of the added organic matter and compaction on them) becomes possible even within limited research-budgeting circumstance.

Table 2 Cost estimation over the measurement apparatus (in thousand Japanese yen).

	Developed Method	Common Method
***D_p/D_0* :**		
Slider compartment	–	164.8+
Main skeleton	25.0+	–
Chamber	14.5+	14.5+
Mesh plate	4.5+	–
O_2 sensor	25.0*	25.0*
Others (valve, pipe, etc.)	9.0¶	7.0¶
***k_a* :**		
Mass flow meter	–	100.0*
Pressure sensor	–	50.0*
Air pump	–	50.0*
Large glass bottle	80.0*	–
Others (valve, pipe, etc.)	10.0¶	10.0¶
Total amount :	**168.0**	**421.3**

+ estimation made by local ironworks

* market price (mostly appeared as middle prices)

¶ estimation made by the authors

Acknowledgement

The authors would like to thank Mr. Syun Arai and Ms. Yuko Hori for their kind support and assistances during the experimental part of this study.

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要　　旨

単一の土壌円筒についてガス拡散係数と通気係数を連続的に測定するための単純で安価な方式を開発した．拡散係数の測定は従来のスライド方式に代えて，試料（内径 10 cm，高さ 6 cm）と拡散室（内径 11 cm，高さ 5 cm）の間に設けた網板にプラスティック・フィルム製のシャッターをグリースで貼りつけ，これを引き落とす方法によった．円環形と円形のシャッターを組み合わせることにより，開放を確実にすることができた．通気係数の測定はマリオット瓶で発生させた負圧を利用して行った．通気量はマリオット瓶中の空気の体積と圧力の測定結果から計算した．豊浦砂について測定したガス拡散係数と通気係数の値は既往の研究と近似し，新方式は有用であると判断された．新方式により装置の製作費は 40 %に低減すると見積もられた．

キーワード：ガス拡散係数，通気係数，測定