Relationship Between Solute Diffusion Coefficient and Electrical Conductivity Under Extremely Low Soil Water Conditions

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Abstract

The relative diffusion coefficient (D_r) of solutes in soils is directly proportional to the “ n th” power of the volumetric soil water content (θ), where n is an empirical parameter, which normally ranges between 1 and 2. The existence of a breakpoint (θ_{br}) in the relationship between θ and D_r has been demonstrated at low- θ , in which the value of n becomes approximately 4 when $\theta < \theta_{br}$. The change in n can be attributed to various mechanisms, including drastic changes in the geometrical distribution of pore liquid water caused by dehydration. However, as direct D_r measurements require considerable time to render sufficient data at low- θ , few studies have measured D_r at $\theta < \theta_{br}$, and the relationship between D_r and θ at $\theta < \theta_{br}$ remains unclear. In this study, we investigated if the indirect D_r measurement method can be applied in the low- θ region of $\theta < \theta_{br}$. An indirect method for measuring D_r was employed to determine the soil electrical conductivity (EC_s). Using dune sands in which the presence of θ_{br} was confirmed, D_r from high- to low- θ was calculated based on EC_s measurements and compared with directly measured D_r . The relationships between θ and D_r calculated based on EC_s and using the transient state method were almost the same. D_r could be calculated from EC_s even at $\theta < \theta_{br}$. The results confirmed that the indirect D_r measurement method can be applied for the low- θ region of $\theta < \theta_{br}$.

Keywords Solute diffusion coefficient in soil · Relative diffusion coefficient of solute in soil · Soil electrical conductivity · Percolation model · Dune sand

1 Introduction

The solute diffusion coefficient in soil, D_p , is one of the important parameters for predicting salt and nutrient transfer and contaminant transport as well as for the use of contaminant remediation studies, risk assessments, and waste disposal management. D_p is defined by Fick’s first law, which states that the solute diffusion flux in soil is proportional to the macroscopic concentration gradient, while the proportionality coefficient is equal to the diffusion coefficient, as shown in Eq. (1) below.

$$J = -\theta D_p(\theta) \frac{\partial C}{\partial x} \quad (1)$$

where J is the solute flux, θ is the volumetric water content, C is the concentration of the solute in the soil solution, and x is the distance. D_p is expressed as follows:

$$D_p(\theta) = \alpha \gamma \tau_d(\theta) D_o \quad (2)$$

where D_o is the solute diffusion coefficient in bulk water, α is a factor that accounts for the increase in drag caused by the higher viscosity of water closer to particle surfaces, γ is a factor representing the electrostatic forces on charged diffusing substances, and $\tau_d(\theta)$ is the diffusive tortuosity factor (Olsen et al. 1965).

However, notably, some studies have used D_p^* , which includes the effect of θ in the solute diffusion coefficient in soil. The relationship between D_p and D_p^* can be expressed by the following equation:

$$D_p^* = D_p / \theta \quad (3)$$

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The empirical relationship between the relative diffusion coefficient of solute in soil, D_r ($D_r = D_p/D_o$), and θ can be represented as follows:

$$D_r = k\theta^n \quad (4)$$

where k and n are empirical parameters. The impedance factor, f , which is defined as the liquid phase impedance factor (Porter et al. 1960), is the same as D_r .

Several previous studies have reported that the value of n at higher θ ranges approximately between 1 and 2 (Barraclough and Tinker 1981; Olsen et al. 1965; Olesen et al. 1996; Porter et al. 1960; So and Nye 1989). This experimental n value range can be explained through physical tortuosity models, including a simple tortuosity (Papendick and Campbell 1981) or percolation model (Ewing and Horton 2003; Hunt and Ewing 2003), where factors α and γ can be neglected (Olsen et al. 1965).

In contrast, only limited studies have measured D_r at low θ (Hamamoto et al. 2009; Mehta et al. 1995; Miyasaka et al. 2014; Rowell et al. 1967; Tokunaga et al. 2017). Mehta et al. (1995) reported a breakpoint (θ_{br}) in the relationship between θ and D_r at low θ in single-grained soil (Shonai dune sand) or aggregated soil (Kanto loam). The breakpoints occur at around $D_r = 0.1$ for both soils, and θ_{br} values correspond to a matric potential value of 0.1 MPa (Mehta et al. 1995). The value of n is ~ 1 at $\theta \geq \theta_{br}$, but it is ~ 4 at $\theta < \theta_{br}$. Most of the soil solution at $\theta < \theta_{br}$ would exist in electrically charged double layers on the surface of the solid particles. Therefore, molecular ion diffusion would be restricted in this solution compared with bulk solution. Thus, the value of γ in Eq. (2), which is negligible at high θ , can have an effect at low θ .

Miyasaka et al. (2014) measured the diffusion coefficient of electrolyte solutes (NaCl and CaCl₂) in soil, which may be affected by soil surface charges, as well as non-electrolyte solutes (glycerin; C₃H₅[OH]₃), which should not be affected by soil surface charges, over a wide range of water content conditions in Shonai dune sand and Kanto loam. These experiments demonstrated that the D_r value for all the analyzed solutes was largely equal even at $\theta < \theta_{br}$, indicating that the observed sharp decline in D_r with low θ in the studied soils should not be attributed to the electric charge on the particle surface. Instead, Miyasaka et al. (2014) suggested that these sharp declines should be attributed to other mechanisms, such as pronounced changes in the geometrical distribution of pore liquid water due to dehydration. Therefore, the percolation model (n value in Eq. (4) ranges from 1 to 2) can be only applied at $\theta \geq \theta_{br}$, where the pore water in the soil exhibits large-scale continuity, and not at $\theta < \theta_{br}$, where the large-scale continuity in pore water disappears. The different model (n value in Eq. (4) is ~ 4) should be applied at low θ (Miyasaka et al. 2014; Yang et al. 2016).

Several studies have measured D_r using a transient-state method, in which concentration profiles were measured in soil columns initially exhibiting step-shaped profiles (Mehta et al. 1995; Miyasaka et al. 2014; Robin et al. 1980; Rowell et al. 1967). However, maintaining appropriate boundary conditions for direct steady-state techniques poses several important challenges (Conca and Wright 1990). Furthermore, column rotation was required to prevent convective soil water flow caused by density differences in the soil solution (Mehta et al. 1995; Rowell et al. 1967). This rotation may have led to gravity-mediated soil water flow at high θ near saturation, thus causing transversal dispersion and an overestimation of the solute diffusion coefficient (Miyasaka et al. 2014). Additionally, the transient-state method requires an inordinate amount of time to render sufficient data at low θ .

The most widely used indirect method is the measurement of soil electrical conductivity (EC_b) (Abderrahmene et al. 2017; Bezzar and Ghomari 2013; Conca and Wright 1992; Garrouch et al. 2001; Mojid et al. 2007). This is a simple, rapid, and inexpensive method for D_r detection. Using this method, D_r can be estimated by measuring EC_b using the Nernst–Einstein equation (Conca and Wright 1992). However, although some studies have measured D_r in rocks at low θ using the indirect method (Conca and Wright 1992), very few studies have measured D_r in soils at low θ where the percolation model cannot be adapted.

Here, the relationship between D_r and θ was determined by measuring the electrical conductivity of Shonai dune sand over a wide range of soil moisture contents. The results were compared with the directly measured relationship between D_r and θ by Miyasaka et al. (2014). We then examined the feasibility of deriving D_r from EC_b measurements at low soil θ wherein the percolation model cannot be applied.

2 Materials and Methods

2.1 Relationship Between the Solute Diffusion Coefficient in Soil and the Soil Electrical Conductivity

Although the liquid phases of soil particles have a complex structure, the EC_b of any part of soil particles is inversely proportional to the path length of the ion and directly proportional to the cross-sectional area of the liquid phase (Rhoades et al. 1976). Therefore, EC_b can be expressed by the following equation using the electrical conductivity of bulk soil solution, EC_w, and electrical conductivity of the surface layer of soil particles (EC_s):

$$EC_b = \theta EC_w T(\theta) + EC_s \quad (5)$$

where $T(\theta)$ is the transmission coefficient (Rhoades et al. 1976). $T(\theta)$ accounts for the tortuous nature of the current lines and any decreases in the mobility of ions near the solid–liquid interface (Rhoades et al. 1976).

$$T(\theta) = \beta \tau_e(\theta) \quad (6)$$

where $\tau_e(\theta)$ is the electrical tortuosity, and β is a factor that accounts for decreases in the mobility of ions near the solid–liquid interface. At high θ , β in Eq. (6) can be ignored. Moreover, EC_s can be ignored in soils that contain small amounts of clay (e.g., sandy soil). Therefore, at high θ , EC_b can be expressed as follows:

$$EC_b = \theta EC_w \tau_e(\theta) \quad (7)$$

Given that $\tau_e(\theta) = \tau_d(\theta)$ (Ghanbarian et al. 2013), the relationship between the relative soil electrical conductivity, EC_r ($= EC_b / EC_w$), and D_r at high θ can be expressed as follows:

$$\frac{EC_r}{\theta} = \tau_e(\theta) = \tau_d(\theta) = D_r = k\theta^n \quad (8)$$

where n ranges from 1 to 2.

At low θ , where the percolation model cannot be applied, the relationship between EC_r ($= EC_b / EC_w$) and D_r can also be expressed by Eq. (8) under the assumption that α in Eq. (2) and β in Eq. (7) are equal, but n in Eq. (8) is approximately 4.

2.2 Four-Electrode Sensor Structure

EC_b was measured using a four-electrode sensor (Inoue and Shiozawa 1994; Rhoades and Ingvalson 1971). Four stainless-steel rods were inserted in parallel into an acrylic column of height 50 mm and inner diameter 50 mm (Fig. 1). The two outer stainless-steel rods acted as current feed (i) electrodes, whereas the other two inner rods were used to measure voltage (V_2). The two outer rods were connected to the resistance (r).

The ratio of the electric current in the outer rods to the electric potential difference of the inner rods (i/V_2) was proportional to EC_b , as shown in the following equation:

$$EC_b = G_c \frac{i}{V_2} = G_c \frac{(V_1/V_2)}{r} \quad (9)$$

where G_c is the sensor constant. V_1 is the voltage of resistance, r ($V_1 = ir$).

The ratio of V_1 to V_2 (V_1/V_2) was measured using a data logger (model 21X, Campbell Scientific Instruments). A 1-kHz square wave was used as the AC voltage, whereas 100 and 3 k Ω resistance values were used at lower and higher θ values, respectively.

Fig. 1 Schematic diagram of the four-electrode sensor (Inoue and Shiozawa, 1994)

A sensor constant G_c was calculated by measuring the electrical conductivity of 1.0 mol/L NaCl solution using an electroconductivity meter (MPC227 Dual Purpose Conductivity/PH/T Meter: Meter Toledo International, Inc.) as well as its V_1 to V_2 ratio at 25 °C using the above-described four-electrode sensor.

2.3 Measurement of Electrical Conductivity of the Soil Samples

Shonai dune sand (i.e., sandy soil with low clay content) obtained from the Shonai Sand Dunes in Yamagata Prefecture, Japan, as in Mehta et al. (1995) and Miyasaka et al. (2014), was used in the experiment (Table 1).

As EC_b with very low water content hardly conducts electricity, high-concentration solution should be used for measurement. Inoue and Shiozawa (1994) investigated the relationship between EC_b and EC_w under the constant θ using clay and salt-removed sand and reported that the relationship between EC_b and EC_w can be expressed by a linear equation at soil solution concentrations between 0.05 and 1 mol/L. Therefore, in this study, the sand was oven-dried, divided into seven equal parts, and placed in double-layered plastic bags, and subsequently, a pre-determined amount of 1.0 mol/L NaCl solutions was added to each bag. After the sands were mixed, they were left undisturbed for more than 24 h to equilibrate. The sands were then uniformly packed into the column comprising the four-electrode sensor so that the soil bulk density was approximately 1.36 g/cm³ (Fig. 1). The sensor was placed in a chamber at 25 °C. After the central temperature of the soil samples reached 25 °C, the V_1/V_2 ratio was measured at 1-min intervals for at least 15 min, and the average value was obtained. After the measurement, the sand in

the sensor was put back into the double-layered plastic bag. The same process was then repeated two more times, for a total of three measurements of the V_1/V_2 ratio.

Next, soil θ in the sensor was measured using a gravimetric method with oven drying. This method involves weighing the moist sand in the column, oven-drying it at 105 °C for 24–48 h, reweighing, and then calculating the mass of water lost as a percentage of the mass of the dried soil as follows:

$$w_c = \frac{M_w - M_d}{M_d} \quad (10)$$

where w_c is the soil water content (g/g), M_w is the mass of moist soil (g), and M_d is the mass of the dried soil (g).

The volumetric water content, θ , was calculated by dividing the mass of water lost in the column (i.e., $M_w - M_d$) by the volume of the column (Fig. 1, height, 50 mm; inner diameter, 50 mm).

The θ values of the soil samples were approximately 0.025, 0.032, 0.042, 0.050, 0.066, 0.080, and 0.270 cm³/cm³.

2.4 Calculation of the Solute Diffusion Coefficient in Soil

EC_b was calculated to substitute the measured V_1/V_2 ratio of the soil samples as well as the resistance (r) and sensor constant (G_w) in Eq. (9). Similarly, the electrical conductivity of 0.1 mol/L NaCl solution at 25 °C was calculated based on the V_1/V_2 ratio of the solution analyzed with the four-electrode sensor instead of the measured V_1/V_2 ratio of the soil samples.

3 Results and Discussion

The relationships between D_r ($=EC_r/\theta$) and θ measured by the indirect method are illustrated in Fig. 2. The breakpoint existed at $\theta_{br}=0.039$ cm³/cm³, and the n values in Eq. (8) were 0.9 at $\theta \geq 0.039$ and 5.9 at $\theta < 0.039$. The relationships between D_r and θ measured directly by Miyasaka et al. (2014) are illustrated in Fig. 3. The breakpoint existed at $\theta_{br}=0.037$ cm³/cm³, and the n values in Eq. (4) were 0.7 at $\theta \geq 0.037$ and 3.8 at $\theta < 0.037$. Although the breakpoints slightly differed between the direct method and soil electrical conductivity method and the values of n at $\theta \geq \theta_{br}$ and $\theta < \theta_{br}$ also slightly differed, we found that the measurement of soil electrical conductivity could indicate the existence of the breakpoint. The relationship between D_r directly

measured by Miyasaka et al. (2014) and D_r calculated by substituting the value of θ measured using the direct method described by Miyasaka et al. (2014) into the equation of D_r - θ derived from the EC_b measurement method is shown in Fig. 4. The dotted line in Fig. 4 shows D_r ($=0.067$) at the breakpoint ($\theta_{br}=0.039$). Although the values of D_r measured using the direct method (Miyasaka et al. 2014) and calculated from the equation for the measurement of EC_b were different around the breakpoint, the overall correlation coefficient was 0.950, indicating a markedly strong correlation.

Bezzar and Ghomari (2013) and Garrouch et al. (2001) reported that it was possible to estimate the solute diffusion coefficient by measuring electrical conductivity of saturated soil water using sand bentonite clay mixture and sandstone rock, respectively. Our findings also demonstrated that the indirect method can be used to measure D_r in soils with high θ (where the percolation model can be applied) as well as low θ (where the percolation model cannot be applied).

Hamamoto et al. (2009), Olesen et al. (1999), Mojid et al. (2007), and Porter et al. (1960) measured f in various soils with low θ and reported that the relationship between f and θ is expressed by a linear function. In contrast, the results reported by Rowell et al. (1967), who measured f at extremely low soil θ , could not be approximated by a linear function and could be approximated by Eq. (4), as shown in the present study; the value of n in Eq. (4) was 2.2 and 5.6 in soils with high and low θ , respectively. In the studies conducted by Mehta et al. (1995), and Miyasaka et al. (2014), the value of n in Eq. (4) ranged from 1 to 2 when the value of D_r was greater than 0.1; the value of n was approximately 4 when the value of D_r was less than 0.1. However, in the results reported by Rowell et al. (1967), the value of n differed depending on whether the value of D_r ($=f$) was larger or smaller than 0.01. There is a possibility that the value of D_r ($=f$) measured by Hamamoto et al. (2009), Olesen et al. (1999), Mojid et al. (2007), and Porter et al. (1960) cannot be approximated only by the linear function at extremely low soil θ . Therefore, the behavior of D_r at extremely low soil θ could be clarified in more detail using the indirect method (Fig. 5).

Although the dune sand used in this study was almost clay-free, the electrical conductivity of the surface of clay particles cannot be ignored when soil containing a large amount of clay is used (Mojid et al. 2007). Therefore, when the solute diffusion coefficient in the soil is estimated based on EC_b measured at low soil θ , the coefficient may be overestimated. Thus, this effect needs to be eliminated.

Table 1 Physical properties of the soil samples used in the experiments conducted by Mehta et al. (1995)

Soil	Particle size distribution [% contribution to total]			Saturated water content [cm ³ /cm ³]	Saturated hydraulic conductivity [cm/s]	Specific surface area [m ² /g]
	Sand	Silt	Clay			
Shonai dune sand	93.3	1.0	5.7	0.43	1.09×10^{-2}	22.1

Fig. 2 Relationship between relative soil electrical conductivity/volumetric water content, EC_r/θ , which is equal to the relative diffusion coefficient and volumetric water content, θ , on a (a) log–log scale and (b) linear scale

Fig. 3 Relationship between directly measured relative diffusion coefficients, D_r , and volumetric water content, θ , (Miyasaka et al. 2014) on a (a) log–log scale and (b) linear scale

4 Conclusion

Some studies have reported the existence of a breakpoint (θ_{br}) in the relationship between θ and D_r at low θ , and that the value of n becomes approximately 4 when $\theta < \theta_{br}$. This change in the n value can be attributed to various mechanisms, including drastic changes in the geometrical distribution of pore liquid water caused by dehydration.

The transient-state method is typically used for measuring D_r . However, it requires considerable time to render sufficient data at low θ , so few studies have measured D_r at $\theta < \theta_{br}$, and the relationship between D_r and θ at $\theta < \theta_{br}$ has not been adequately discussed. An indirect method for measuring D_r is to determine the ECs. However, previous studies have not confirmed if this method is applicable at $\theta < \theta_{br}$. Therefore, we calculated the solute diffusion coefficient in soil based on ECs measurements of high- and low- θ sand, wherein the presence of θ_{br} was confirmed. The results showed that the relationship between D_r and θ calculated based on ECs was almost the same as that measured using the transient state method, and D_r can be calculated from ECs even at $\theta < \theta_{br}$.

Fig. 4 Relationship between relative soil electrical conductivity/volumetric water content, EC_r/θ , which is equal to the relative diffusion coefficient and D_r calculated from the relational expression between D_r and θ derived from the direct method (Miyasaka et al. 2014)

Fig. 5 Compilation of literature on relative diffusion coefficient, D_r (=impedance factor, f), as a function of volumetric water content. The figures on the left ((a), (c), (e), and (g)) are on log–log scale, whereas the figures on the right ((b), (d), (f), and (h)) are on a linear scale. These data are obtained either from the tabulation or digitization of figures published in the cited studies

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Data Availability The data can be made available upon request.

Code Availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

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References

- Abderrahmene M, Abdelillah B, Fouad G (2017) Electrical prediction of tortuosity in porous media. *Energy Procedia* 139:718–724. <https://doi.org/10.1016/j.egypro.2017.11.277>
- Barracough PB, Tinker PB (1981) The determination of ionic diffusion coefficients in field soils. I. Diffusion coefficients in sieved soils in relation to water content and bulk density. *J Soil Sci* 32:225–236. <https://doi.org/10.1111/j.1365-2389.1981.tb01702.x>
- Bezzar A, Ghomari F (2013) Monitoring of pollutant diffusion into clay liners by electrical methods. *Transp Porous Media* 97:147–159. <https://doi.org/10.1007/s11242-012-0115-9>
- Conca JL, Wright J (1990) Diffusion-coefficients in gravel under unsaturated conditions. *Water Resour Res* 26:1055–1066. <https://doi.org/10.1029/WR026i005p01055>
- Conca JL, Wright J (1992) Diffusion and Flow in gravel, soil, and whole rock. *Applied Hydrogeology* 1:5–24. <https://doi.org/10.1007/PL00010963>
- Ewing RP, Horton R (2003) Scaling in diffusive transport. In: Pachepsky Y et al (eds) *Scaling methods in soil physics*. CRC Press, Boca Raton, FL, pp 49–61
- Garrouch AA, Liaqat A, Qasem F (2001) Using diffusion and electrical measurements to assess tortuosity of porous media. *Ind Eng Chem Res* 40:4363–4369. <https://doi.org/10.1021/ie010070u>

- Ghanbarian B, Hunt AG, Ewing RP, Sahimi M (2013) Tortuosity in Porous Media: A Critical Review. *Soil Sci Soc Am J* 77:1461–1477. <https://doi.org/10.2136/sssaj2012.0435>
- Hamamoto S, Perera MSA, Resurreccion A, Kawamoto K, Hasegawa S, Komatsu T, Moldrup P (2009) The solute diffusion coefficient in variably compacted, unsaturated volcanic ash Soils. *Vadose Zone J* 8:942–952. <https://doi.org/10.2136/vzj2008.0184>
- Hunt AG, Ewing RP (2003) On the vanishing of solute diffusion in porous media at a threshold moisture content. *Soil Sci Soc Am J* 67:1701–1702. <https://doi.org/10.2136/sssaj2003.1701>
- Inoue M, Shiozawa S (1994) Measurement of electrical conductivity in soil columns by the four-electrode method and its application. *Soil Phys. Cond Plant Growth, Jpn* 70:23–28
- Mehta BK, Shiozawa S, Nakano M (1995) Measurement of molecular diffusion of salt in unsaturated soils. *Soil Sci* 159:115–121. <https://doi.org/10.1097/00010694-199502000-00006>
- Miyasaka K, Shiozawa S, Nishida K, Yoshida S (2014) Solute electrical charge effects on molecular diffusion coefficients in unsaturated soils. *Soil Sci Soc Am J* 78:1852–1858. <https://doi.org/10.2136/sssaj2014.05.0201>
- Mojid MA, Rose DA, Wyseure GCL (2007) A model incorporating the diffuse double layer to predict the electrical conductivity of bulk soil. *Eur J Soil Science* 58:560–572. <https://doi.org/10.1111/j.1365-2389.2006.00831.x>
- Olesen T, Moldrup P, Gamst J (1999) Solute diffusion and adsorption in six soils along a soil texture gradient. *Soil Sci Soc Am J* 63:519–524. <https://doi.org/10.2136/sssaj1999.03615995006300030014x>
- Olesen T, Moldrup P, Henriksen K, Petersen LW (1996) Modeling diffusion and reaction in soils: IV. New models for predicting ion diffusivity. *Soil Sci* 161:633–645. <https://doi.org/10.1097/00010694-199610000-00001>
- Olsen SR, Kemper WD, Van Schaik JC (1965) Self-diffusion coefficients of phosphorus in soil measured by transient and steady-state methods. *Soil Sci Soc Am J* 29:154–158. <https://doi.org/10.2136/sssaj1965.03615995002900020014x>
- Papendick RI, Campbell GS (1981) Theory and measurement of water potential. In: Parr JF, Gardner WR, Elliott LF (eds), *Water Potential Relations in Soil Microbiology*, *Soil Sci Soc Am J*, Madison 1–22. <https://doi.org/10.2136/sssaspecpub9.c1>
- Porter LK, Kemper WD, Jackson RD, Stewart BA (1960) Chloride diffusion in soils as influenced by moisture content. *Soil Sci Soc Am J* 24:460–463. <https://doi.org/10.2136/sssaj1960.03615995002400060014x>
- Rhoades JD, Ingvalson RD (1971) Determining salinity in field soils with soil resistance measurements. *Soil Sci Soc Am J* 35:54–60. <https://doi.org/10.2136/sssaj1971.03615995003500010020x>
- Rhoades JD, Raats PAC, Prather RJ (1976) Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. *Soil Sci Soc Am J* 40:651–655. <https://doi.org/10.2136/sssaj1976.03615995004000050017x>
- Rowell DL, Martin MW, Nye PH (1967) The measurement and mechanism of ion diffusion in soils III. The effect of moisture content and soil-solution concentration of the self-diffusion of ions in soils. *J Soil Sci* 18:204–221. <https://doi.org/10.1111/j.1365-2389.1967.tb01501.x>
- So HB, Nye PH (1989) The effect of bulk density, water content and soil type on the diffusion of chloride in soil. *J Soil Sci* 40:743–749. <https://doi.org/10.1111/j.1365-2389.1989.tb01314.x>
- Tokunaga TK, Finsterle S, Kim Y, Wan J, Lanzirrotti A, Newville M (2017) Ion diffusion within water films in unsaturated porous media. *Environ Sci Technol* 51:4338–4346. <https://doi.org/10.1021/acs.est.6b05891>
- Yang R, Lemarchand E, Fen-Chong T (2016) A micromechanics model for solute diffusion coefficient in unsaturated granular materials. *Trans Porous Med* 111:347–368. <https://doi.org/10.1007/s11242-015-0597-3>

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