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Water-entry value as an alternative indicator of soil water-repellency and wettability

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Abstract

Soil water-repellency is an increasingly important consideration in hydrology. In this paper, we relate the degree of soil water-repellency and wettability to the critical water-entry value of a soil. A water-ponding method was used for simple measurement of water-entry value in repellent soils. A tension–pressure infiltrometer method was demonstrated for measuring water-entry value in both repellent and wettable soils. The measurement techniques were used to detect a sudden breakdown of repellency under a sufficiently high water pressure. Experimental results have proven that the water-entry value, in terms of soil water potential, is positive in repellent soils, and negative in wettable soils or soil conditions. The water-entry value is shown to be an easily measured indicator of repellency or wettability that provide an assessment of hydraulic effects of soil physical, chemical and biological properties. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Soil water-repellency; Water-entry value; Tension–pressure infiltrometer method

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1. Introduction

Soils containing large amount of hydrophobic materials (plant litter and residues, organic fertilizers and pesticides, etc.) may become water repellent or less wettable. The degree of repellency and wettability is traditionally judged using the water–solid contact angle (γ). A soil is classified as being water repellent if $\gamma > 90°$ and water wettable if $\gamma < 90°$. However, due to gradual breakdown of soil water-repellency and the granular soil surface condition, direct measurement of the contact angle has not been possible. Presently, many indirect methods are used to measure soil water-repellency.

The simplest and most common and practical method used to measure water-repellency is the water drop penetration time (WDPT) test (Van't Woudt, 1959, 1969; Letey, 1969). Three drops of distilled water from a standard medicine dropper are placed on the smoothed surface of a soil sample, and the time that elapses before the drops are adsorbed is determined. A soil is considered to be water repellent if the WDPT exceeds 5 s (Bond and Harris, 1964; DeBano, 1969), which reflects the gradual breakdown of the soil water-repellency. Based on this method, Dekker and Ritsema (1994) classified the Holland soils into five repellency classes: (1) wettable soil for $WDPT < 5$ s; (2) slightly water repellent soil for $\mathrm{WDPT} = 5 - 60$ s; (3) strongly water repellent soil for $\mathrm{WDPT} = 60 - 600$ s; (4) severely water repellent

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soil for $\mathrm{WDPT} = 600 - 3600$ s; and (5) extremely water repellent soil for $\mathrm{WDPT} > 3600$ s.

Another common method for characterizing soil water-repellency is the alcohol percentage (AP) test (Letey, 1969; Watson and Letey, 1970). Water containing increasing concentrations of ethanol is applied in drop form to the surface of soil samples until a concentration is reached where immediate infiltration occurs. A high concentration indicates severe water repellency. While the water drop penetration time was designed to measure the gradual breakdown of repellency, the alcohol percentage test was used to induce and measure the instantaneous breakdown of repellency.

In this paper, we use water-entry value as an alternative indicator of soil water-repellency. By first imposing a low hydraulic pressure at the soil surface to prevent initial wetting of the soil and then increasing the pressure, a critical pressure (or water-entry value) was observed at the instantaneous breakdown of repellency or the start of infiltration. A water-ponding (WP) method was used for measuring the water-entry values of repellent soils, and a tension-pressure infiltrometer (TPI) method for measuring water-entry values in both wettable and repellent soils. Sample experimental results are presented to show the effects of soil initial moisture and organic matter contents on the change of water-entry value.

2. Hydraulics of repellency and wettability

2.1. Water-entry and air-entry values

The concepts of entry or bubbling pressures are used in fluid mechanics to characterize the start of fluid–fluid displacement in a porous medium (Bear, 1972). When a wetting fluid starts to displace a nonwetting fluid initially saturating the porous medium, the displacement capillary pressure (or suction) is called the wetting-fluid bubbling or entry value. Inversely, when a nonwetting fluid ($\gamma > 90°$) starts to displace a wetting fluid, the threshold capillary pressure is called the nonwetting-fluid bubbling or entry value. The capillary pressure (h_c) is defined as

$$h_c = h_{nw} - h_w \tag{1}$$

where h_w is the wetting fluid pressure at the fluid–fluid interface, and h_{nw} is the nonwetting fluid pressure at the interface. In the unsaturated zone, water is the wetting fluid and air is the nonwetting fluid. In a hydrophobic porous medium, however, water becomes a nonwetting fluid and air is the wetting fluid. If the soil air pressure h_{nw} below the wetting front is zero (i.e. at the atmospheric pressure), the capillary pressure is given by

$$h_c = -h_w \tag{2}$$

Thus, the water-entry value (h_{we}) and air-entry value (h_{ae}), in terms of capillary pressure heads, are equivalent to the negative of soil water potential. In this paper, we choose to express the entry values in soil water potentials for conveniences of hydraulic considerations. The water-entry value (h_{we}) is hitherto referred to as the critical soil water potential (h_w) at which water starts to displace air in the porous medium. The air-entry value (h_{ae}) is then the critical soil water potential (h_w) at which air starts to displace water in a porous medium. Therefore, the infiltration process involves water-entry at the wetting front and the drainage process involves air-entry at the soil surface. Detailed analyses of the entry values were also described by other authors (Bear, 1972; Hillel, 1980; Hillel and Baker, 1988; Jury et al., 1991; Kutilek and Nielsen, 1994).

Since water-entry value is the threshold for infiltration, and air-entry value for drainage, entry values can be estimated from the soil water retention curves (SWRCs). Although many authors have proposed various methods for estimating the values of h_{we} and h_{ae} based on SWRCs (Bouwer, 1964, 1966; Brooks and Corey, 1966; Mein and Larson, 1973; Morel-Seytoux and Khanji, 1974; Neuman, 1976; Brakensiek, 1977; Morel-Seytoux et al., 1996; Wang et al., 1997), these methods were found to result in very similar average values of h_{we} and h_{ae} (Mein and Larson, 1973; Wang et al., 1997). According to the most recent study of Wang et al. (1997), the values of h_{we} and h_{we} corresponding to the inflectional capillary pressure, h_c^*, on the wetting retention curve and the drainage retention curve, respectively, can

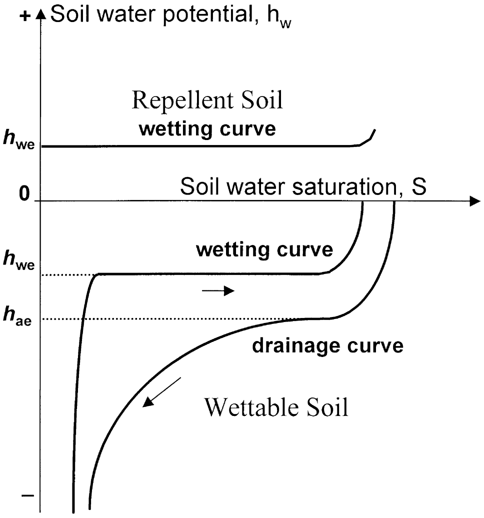


Fig. 1. Soil water retention curves for a wettable and a repellent soil. The h_{we} and h_{ae} denote water-entry and air-entry values of the porous soils, respectively.

be determined using

$$h_c^* = \frac{1}{\alpha}\left[\frac{n-1}{n(m+1)-n+1}\right]^{1/n} = \begin{cases} m^{1/n}/\alpha & \text{for } m = 1 - 1/n \\ 1/\alpha & \text{for } m = 1 - 2/n \end{cases} \tag{3}$$

The corresponding water saturation, S_e^*, on the retention curves can be calculated using

$$S_e^* = \left[1 - \frac{n-1}{n(m+1)}\right]^{m} = \begin{cases} (1+m)^{-m} & \text{for } m = 1 - 1/n \\ 0.5^m & \text{for } m = 1 - 2/n \end{cases} \tag{4}$$

where, α, m and n are parameters of Van Genuchten (1980) model for SWRC.

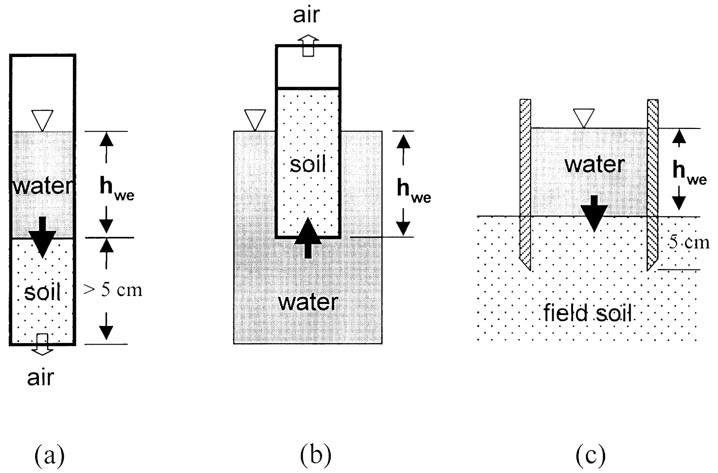
The above SWRC method gives indirect estimations of static entry values for wettable soils. The entry values for a wettable soil can also be directly measured using a pressure infiltrometer method (Fallow and Elrick, 1996). In their method, the soil was initially saturated under positive pressures, then was gradually desaturated until air entry into the infiltrometer. This was followed by water entry into the soil. However, the water-entry value of the soil at the initial water content could not be detected in the process.

In a recent experiment, Wang et al. (1998a) found that the water-entry values for repellent soils were positive ($h_{we} > 0$). An initially repellent soil was not wetted until a critical depth of ponding was reached. This critical ponding depth was considered the water-entry value of the repellent soil, as shown on a positive wetting retention curve in Fig. 1. Since soil water-repellency disappears when the soil is initially saturated or at a high initial water content (Dekker and Ritsema, 1994), the drainage retention curve of a repellent soil should be qualitatively the same as that for a wettable soil. The water-entry value (h_{we}) is clearly affected by soil texture, structure, initial water content and the contact angle (γ). In wettable soils ($\gamma < 90°$), h_{we} was considered being equal to the capillary rise (Kutilek and Nielsen, 1994). In repellent soils, h_{we} should then be equivalent to the capillary drop.

2.2. Potential and actual repellency and wettability

A soil is less wettable when it is dry and contains organic matters. The contact angle increases with the increase of organic matter content. However, the repellent soil becomes wettable when soil water content is above a critical value. The *potential water repellency* was defined and measured on dried samples, whereas the *actual water repellency* was measured on samples with an initial water content (Dekker and Ritsema, 1994). Dekker and Ritsema (1996) also showed that the potential repellency increased with the drying temperature in the oven. The soil became more repellent under a drying temperature of 65°C than under 25°C. Both the soil water-repellency and the critical water content were dependent on the hydrophobic organic matter content in the soil.

For convenience of integrated analyses along with other soil properties (e.g. dry bulk density), we recommend here to measure the potential soil water wettability and potential soil water-repellency on samples dried under 105°C for at least 24 h. The dried samples need to be cooled down to room temperature before measurement for potential water-entry values.The actual soil water-repellency and wettability are



(a) (b) (c)

Fig. 2. WP method for measurement of water-entry value (h_{we}) of a repellent soil (contact angle $\gamma > 90°$) : (a) water ponding on soil surface; (b) equivalent capillary depression method; and (c) Ring insertion in the field.

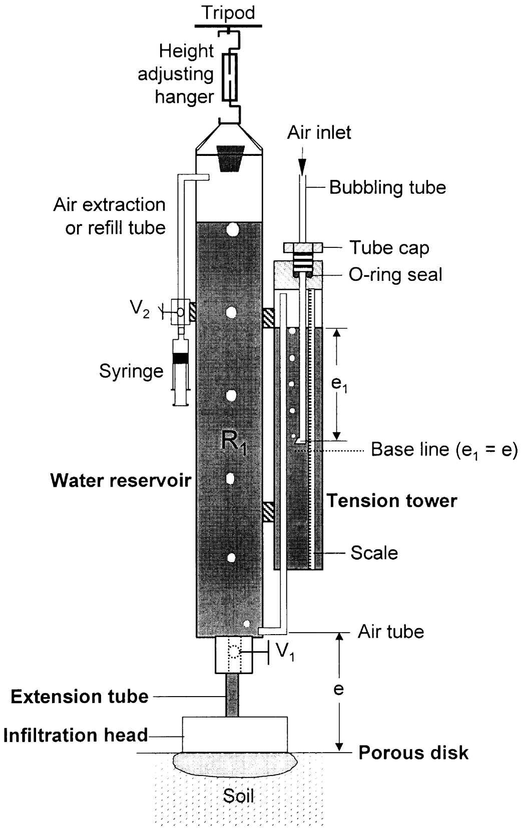


Fig. 3. Tension–Pressure Infiltrometer method for measurement of water-entry value (h_{we}) to quantify the soil water wettability or repellency. V_1 is a two-way valve and V_2 is a three-way valve.

measured under other conditions with initial soil water contents.

3. Methods for measuring water-entry value

3.1. The water-ponding method for measurement of soil water-repellency

In this method, the repellent soil is packed into a transparent tube (2–5 cm i.d.), as shown in Fig. 2a. The inside wall of the test tube should be treated with repellent materials (e.g. Teflon dry film lubricant) before packing to prevent preferential edge flow down the tube. The soil sample should be placed on a porous plate or cheesecloth to prevent air entrapment during the test. The soil surface must be leveled and covered with a filter paper or cheesecloth under the porous plate to prevent soil surface disruption by water flow. By increasing the ponding depth of water on the soil surface (Fig. 2a), one will notice a critical depth at which water suddenly starts to infiltrate into the soil. This critical depth is the water-entry value, h_{we}, of the repellent soil. The magnitude of h_{we} indicates the degree of water repellency. An equivalent method is to lower the transparent tube into the water, as shown in Fig. 2b, the water-entry value equals to the critical capillary depression at which water starts to infiltrate into the soil. The in situ water-entry value of a repellent field soil can be measured by using an insertion ring (5–10 cm i.d.), as shown in Fig. 2c. Water is added to soil surface inside the ring until the water-entry value is observed.

3.2. Tension-pressure infiltrometer method

The water-entry value can also be used to evaluate wettability of a soil. In this case, the soil–water interface is initially provided with a sufficiently high suction to prevent the soil from being wetted. The suction is gradually reduced until water enters the soil. For the purpose of measuring potential and actual wettability ($\gamma < 90°$) in terms of water-entry value at any initial water content, a TPI was designed based on designs of tension infiltrometer (Perroux and White, 1988) and Guelph pressure infiltrometer (Fallow and Elrick, 1996).

As shown in Fig. 3, the TPI is composed of five parts: a transparent Mariotte reservoir R_1, a transparent tension tower R_2, a transparent Vinyl extension tube, a cylinder-shaped infiltration head, and a porous disk glued to the bottom of the infiltration head. This design of TPI is slightly different from the design of a tension infiltrometer (Perroux and White, 1988) where the infiltration disk was a perforated plastic plate wrapped with a layer of Nylon membrane. Since the Nylon cloth was easily broken or clogged at the soil surface, we used a porous ceramic disk in the places of the plastic plate and the Nylon cloth. The capillary air-entry value of the ceramic disks (5 cm in diameter) was in the range of 30–70 cm of water height. The TPI can be hung on a tripod with height adjustment mechanisms to maintain a minimum and constant pressure at infiltration surface (disk–soil interface). The flexible extension tube was used to adjust the infiltration head to achieve good contact between the soil and the infiltration disk.

The soil water pressure at the infiltration surface is regulated in the tension tower by adjusting the height e_1 of the bubbling tube relative to e, the vertical distance between the air tube and the disk surface. When the bubbling tube is set at the "base line" defined by $e_1 = e$, the pressure at the infiltration surface is zero. When $e_1 > e$, a negative pressure head (suction) is imposed, and when $e_1 < e$, a positive pressure head (ponding) will result. The water pressure head (h_0) at the infiltration surface is calculated as

$$h_0 = e - e_1 = e - (z_1 - z_2) \tag{5}$$

where z_1 is the water level in the tension tower and z_2 the water level in the bubbling tube (Fig. 3).

The procedure to measure the wettability (water-entry value) of a soil using a TPI starts from a high negative initial pressure at the soil surface. The specific procedures include: (1) push down the bubbling tube to the bottom of the tension tower; (2) hold the infiltrometer head in the air (i.e. not in contact with or directly above the soil surface), turn off valve V_2, and turn on valve V_1 in sequence (Fig. 3). Water will flow out from the infiltration disk with a decreasing rate; (3) extract air out of the head space of water reservoir R_1 using a syringe attached to valve V_2, until water level, z_2, in the bubbling tube decreased close to (but not exceed) $z_2 = z_1 - e - c$, where c is the air-entry (bubbling) value of the ceramic disk; and (4) turn off valve V_2. Once the infiltrometer head is placed at the soil surface, water will not infiltrate due to the condition $h_0 < h_{\mathrm{we}}$. By gently moving the bubbling tube upward or releasing air through a small needle, soil water potential at the infiltration surface increases. One will notice a critical value of z_2^* and z_1^* (Fig. 3) at which water starts infiltrating with a noticeable flow rate. The critical value $h_0^* = e - (z_2^* - z_1^*)$ is the water-entry value (h_{we}) of the soil (Fig. 3). The value of h_{we} for hydrophobic (or water repellent) soil, although could be easily measured using the WP method (Wang et al., 1998b), can also be measured using TPI following the above procedure. An insertion ring (Fig. 2c) should be attached to the disk head and inserted into the soil. The critical value of $h_0^* = e - (z_2^* - z_1^*)$ for a repellent soil is positive.

3.3. Example measurement results

Both repellency and wettability vary with soil type and with state variables such as initial water, clay and organic matter contents, soil pH values and temperature or fire experiences, the presence of fungal mycelium, and others (Letey et al., 1975). Example measurement results using WP and TPI methods are presented here to demonstrate the effects of initial soil water, clay and organic matter contents on repellency and wettability of selected soils.

Three types of oven-dried soils, a water-repellent coarse sand, a water-wettable fine sand, and a

Table 1
Properties of the packed porous media used for measurement of water-entry value

Medium type	Dry bulk density γ_d (g/cm^3)	Initial water content θ_0 (cm^3/cm^3)	Organic matter content OMC (% wt.)	Clay content CC (%)	Water-entry potential h_{we} (cm H_2O)	Water drop penetration time (min)
Water repellent sands[a]						
1st layer (humose topsoil)	1.41	0	20	<3	12	>60
2nd layer (transitional)	1.54	0	4	< 3	7	10–60
3rd horizon (bottom)	1.59	0	<5	<3	2	1–10
Water wettable sand						
Initially dry	1.52	0	0.15	1.6	-11	0
Initially wet	1.52	0.31	0.15	1.6	-23	0
Wettable loamy sand						
Manure treated (50 ton/ha)	1.61	0	1.12	8	-13	0
Without manure	1.69	0	0.89	10	-25	0

[a] Sands of Ouddorp, The Netherlands.

water-wettable loamy sand (Table 1) were used for determining their potential repellency or wettability. Properties of the three-layer Ouddorp repellent sands were described in detail by Ritsema et al. (1993). The silicon fine sand was purchased from a local store. The loamy sand was taken from an agricultural field in Bakersfield, California. The bulk samples of Bakersfield soil were taken from two neighboring plots: one treated with 50 tons per hectare of dairy manure, the other was not treated with any organic amendment. The water-entry values (h_{we}) of the repellent sands were measured using the water ponding method (Fig. 2a). The entry values of the wettable soils were measured using the TPI method (Fig. 3). As shown in Table 1, the repellent sands exhibited positive water-entry values (h_{we}), and the wettable soils had negative values.

Fig. 4 shows the effects of initial water content on the magnitude of water-entry value. The initially dry silicon sand exhibited a water-entry value $h_{we} = -11$ cm of water (Fig. 4a), whereas the initially wet sand had $h_{we} = -23$ cm of water (Fig. 4b). These two values show the strong dependence of wettability on the initial water content. This also indicates that the unsaturated flow will be more likely to enter the initially wet sand rather than the initially dry sand.

As shown in Fig. 5, soil wettability is also severely affected by the organic matter and clay content. The manure treated loamy sand was less wettable ($h_{we} = -13$ cm, Fig. 5a) than the same soil without manure treatment ($h_{we} = -25$ cm, Fig. 5a). This also reveals that flow in soils are affected by chemical and biological properties. Such compound effects are reflected in the water-entry value.

4. Discussion and conclusions

We presented a hydraulic method to measure repellency and wettability of a soil or any other porous medium. An initially low water pressure is imposed at the soil surface. By gradully increasing the source pressure head, a critical pressure, the water-entry value, is realized at which water starts to infiltrate, overcoming the repellent forces in the soil. The water-entry value is a hydraulic representation of the water drop penetration time. Two simple methods, the WP and TPI method, were developed for quick measurement of soil water-repellency and wettability. Experiments were also conducted to demonstrate the effects of initial soil water, clay and organic matter contents on repellency and wettability.

The magnitude of water-entry value reflects the combined effects of various soil properties and state variables on water mobility in the soil. It is a hydraulic indicator of soil water-repellency or wettability. The water-entry value has been used in many simulation models for predicting infiltration, identifying the onset of wetting front instability, and calculating the size and speed of fingered preferential flow (Morel-Seytoux and Khanji, 1974; Neuman, 1976; Wang et al., 1997, 1998b). The concept can also be directly

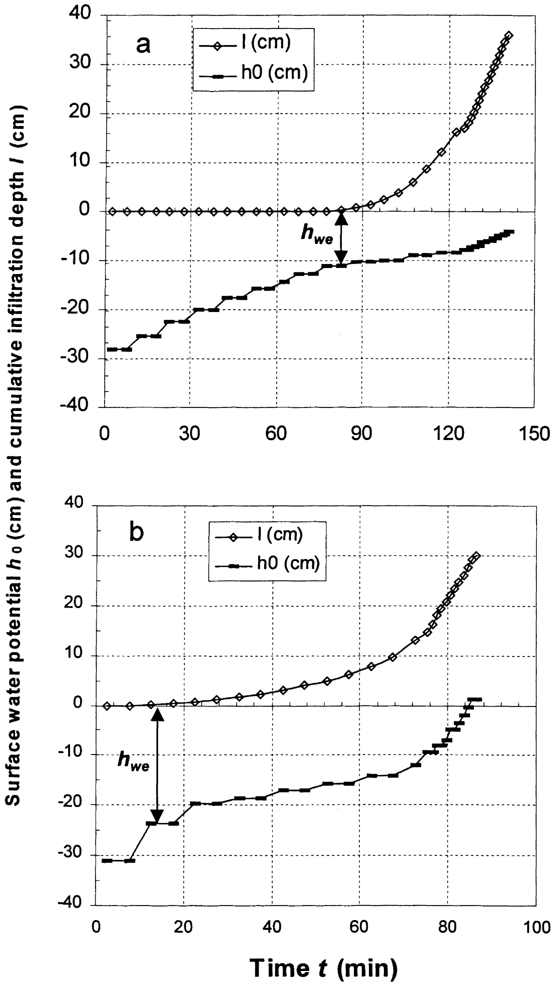


Fig. 4. Water infiltration into: (a) an initially dry sand; and (b) an initially wet sand, showing the effects of initial water content on water-entry value.

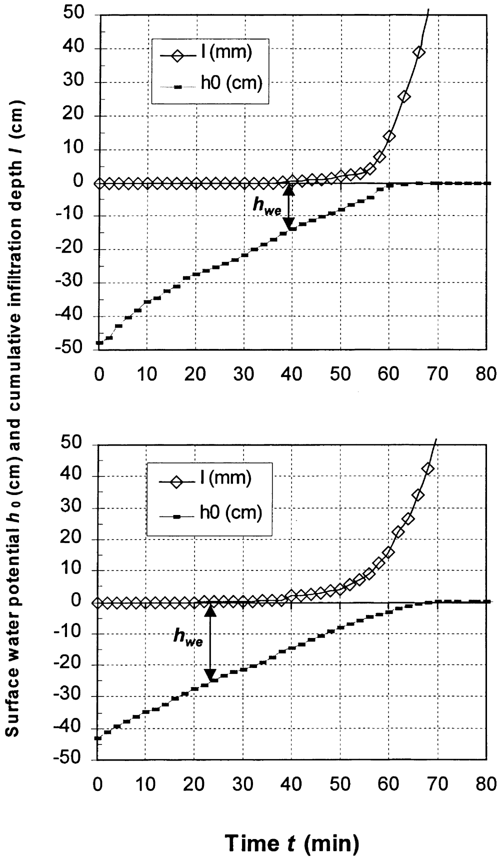


Fig. 5. Water infiltration into: (a) a manure treated loamy sand; and (b) the loamy sand without manure treatment, showing the potential effects of organic mater and clay contents on the magnitude of water-entry value.

used to reduce runoff and increase infiltration in repellent soils by applying a greater depth of water than the water-entry value in the field.

We tend to believe that the potential soil water-repellency and wettability (water-entry value of dry soil) is mainly affected by soil organic matter and clay contents as well as the dry bulk density. Thus, the water-entry value may be empirically predicted utilizing the soil survey data. The actual soil water wettability (water-entry value of wet soil) is altered from the potential water-entry value due to different initial water saturation. This can also be predicted using a functional relation based on theoretical and experimental analyses. The concept of water-entry value can be directly used in hydrologic models. It might also be used in design and practice of surface irrigation where high ponding of water is necessary to enhance infiltration in repellent soils.

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