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Modeling water infiltration in a large layered soil column with a modified Green–Ampt model and HYDRUS-1D

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ABSTRACT

A modified Green–Ampt model was developed in this study to describe water infiltration through a 300-cm long and five-layered soil column. In the modified Green–Ampt model, a saturation coefficient was introduced to determine the water content and hydraulic conductivity of the wetted zone. The saturation coefficient was determined by the ratio between measured moisture volume and total saturated moisture volume of the wetted zone, and it should be less than 1. In this experiment, the calculated saturation coefficient was 0.8. The wetting front suction head was determined by Bouwer and Neuman methods. For comparison, the infiltration process was also simulated by traditional Green–Ampt model and HYDRUS-1D code which was based on the Richards equation. It was found that the traditional Green–Ampt model was unable to describe the infiltration process adequately. The HYDRUS-1D provided good simulation results of infiltration rate and accumulative infiltration. However, it was difficult to track the movement of wetting front along the soil profile and the corresponding root mean square error (RMSE) value was up to 57.17 cm. For the modified Green–Ampt model with Bouwer method, the RMSE values of simulated infiltration rate, accumulative infiltration and wetting front depth were 2.01E−3 cm/min, 1.28 and 8.29 cm, respectively, which were much smaller than those of traditional Green–Ampt model and HYDRUS-1D. Moreover, the modified Green–Ampt model with Bouwer method could adequately capture the infiltration rate, the accumulative infiltration and the movement process of wetting front in the large layered soil column. Therefore, it appears that the modified Green–Ampt model presented in this study is a highly effective approach to simulate water infiltration in layered soils.

1. Introduction

Infiltration has long been a focus of agriculture and water research because of its fundamental role in land-surface and subsurface hydrology, and agricultural irrigation (Milla and Kish, 2006). A large number of mathematical models have been developed to evaluate the computation of infiltration. In general, these infiltration models can be classified into physically based models, semi-empirical and empirical models (Mishra et al., 1999). The semi-empirical and empirical models such as Kostiakov and Horton models are usually derived from either field or laboratory experimental data, and they are always in the form of simple equations (Lei et al., 1988; Mishra et al., 2003). However, the semi-empirical and empirical models cannot provide the detailed information of infiltration process and their physical meaning is not robust. Compared to the semi-empirical and empirical models, the physically based models can substantially describe the detailed infiltration process. Among the physically based models, the most commonly used ones are Richards equation and Green–Ampt model.

The Richards equation was derived using the mass conservation law and Darcy's law (Lei et al., 1988). As a physically based numerical model, the Richards equation has been extended into many complex conditions (Brunone et al., 2003; Pachepsky et al., 2003; Barontini et al., 2007; Elmaloglou and Diamantopoulos, 2008). However, the Richards equation is strongly non-linear and cannot be solved analytically, especially under complex initial and boundary conditions. Consequently, numerical methods such as finite difference and finite element methods have been used to solve Richards equation (Arampatzis et al., 2001). The numerical solution of Richards equation requires an iterative implicit technique with fine discretization in space, which results in tedious solving process (Damodhara Rao et al., 2006). Based on finite element method, the HYDRUS-1D code was developed to solve the Richards equation and was widely used to simulate one-dimensional water movement in variably saturated media (Šimůnek et al., 2005).

The Green–Ampt model (Green and Ampt, 1911) is a simplified representation of the infiltration process. The model assumes that a sharp wetting front separates the soil profile into an upper

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saturated zone and a lower unsaturated zone. The soil water content in the lower unsaturated zone keeps at the initial value. The Green–Ampt model has been verified against some test cases (Idike et al., 1980; Moore and Eigel, 1981) and the Richards equation (Freyberg et al., 1980; Moore, 1981; Ahuja, 1983). The formulation of Green–Ampt model is very simple and the model parameters can be easily obtained from soil physical properties (Brakensiek and Onstad, 1977; Loáiciga and Huang, 2007). Therefore, it has been subjected to a lot of interests and applications in hydrology research. For instance, the Green–Ampt approach has been used in some soil erosion models such as WEEP (Flanagan et al., 2001) and watershed hydrological models such as SWAT (Neitsch et al., 2002).

The Green–Ampt model was originally developed to study infiltration in uniform soils. There were also many efforts about extending Green–Ampt model to simulate infiltration in layered soils (Childs and Bybordi, 1969; Hachum and Alfaro, 1980; Beven, 1984; Selker et al., 1999). Recently, Chu and Mariño (2005) proposed a modified Green–Ampt model to simulate infiltration in a 120-cm depth and four-layered field soil profile under steady rainfall. Damodhara Rao et al. (2006) developed a 1-D infiltration model based on Green–Ampt approach for seal formed layered soils, and used this model to study infiltration in a three-layered system (seal-tillage-subsoil). Liu et al. (2008) derived a Green–Ampt model for layered soils with non-uniform initial water content under unsteady infiltration, and tested this model with data from infiltration experiment in a 90-cm long and two-layered soil column. However, most of the previous studies about Green–Ampt model at laboratory scale were focused on relatively short columns. The scale and number of soil layers were severely limited. To our knowledge, there were little studies about using Green–Ampt model to simulate infiltration in a large layered soil column.

As the versatile and popular use of Green–Ampt model in estimating infiltration, the question of determining the model parameters must be addressed. There are two key parameters in Green–Ampt model. One is the suction head at the wetting front. Several ways have been proposed to determine this parameter from measured soil hydraulic properties (Bouwer, 1969; Neuman, 1976). Another parameter is hydraulic conductivity of the upper saturated zone. As pointed by Brakensiek and Onstad (1977), infiltration was more sensitive to this hydraulic conductivity with respect to the wetting front suction head. In the original Green–Ampt model, the hydraulic conductivity of upper saturated zone was referred to as the saturated hydraulic conductivity. However, this assumption was unrealistic because of entrapped air in the upper saturated zone (Hammecker et al., 2003). Therefore, the hydraulic conductivity used in the Green–Ampt equation was not the actual value of saturated hydraulic conductivity but only a certain fraction of it. Bouwer (1966) suggested that this effective hydraulic conductivity was half of the saturated hydraulic conductivity. However, the method developed by Bouwer (1966) was only an empirical method and its application was greatly limited. In this paper, we developed an approach based on sound physical arguments to determine the effective hydraulic conductivity of the upper saturated zone.

The objectives of this study are to: (1) develop a modified Green–Ampt model to describe water infiltration process in a 300-cm long and five-layered soil column; and (2) compare the modeling results of the modified Green–Ampt model with those of the traditional Green–Ampt model and HYDRUS-1D.

2. Materials and methods

2.1. Infiltration experiment

The infiltration experiment was conducted in a transparent acrylic column (335-cm length, 28-cm inner diameter). The top 15 cm of the column was used for water application. The following 300 cm of the column was packed with five-layered soils. A port located 7.5 cm above the soil surface was connected to a Mariotte bottle (10-cm inner diameter, 50-cm height) to maintain a constant depth of ponding. The schematic diagram of experimental setup is shown in Fig. 1. To our knowledge, the soil column in this experiment is one of the longest columns used for investigating infiltration in layered soils at laboratory scale.

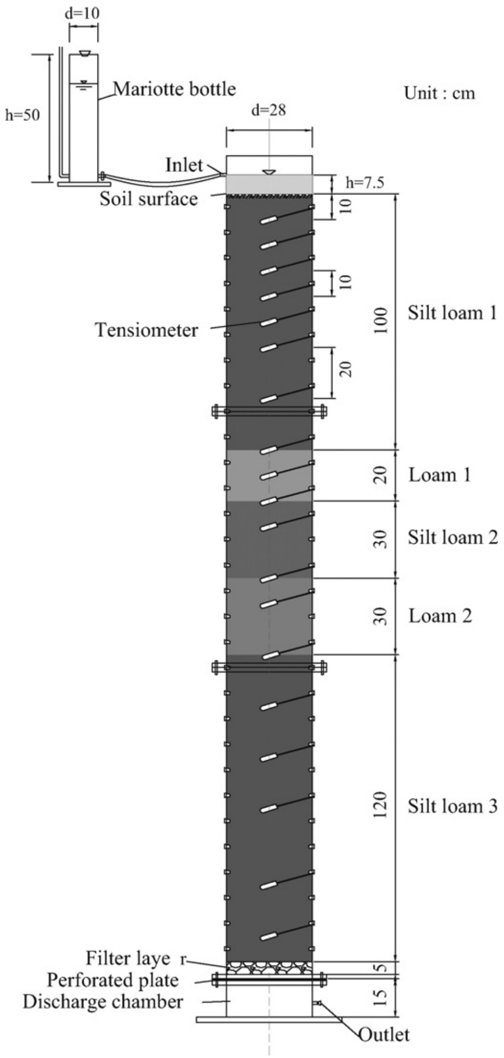

Fig. 1. Schematic representation of the experimental setup used in this study.

Five different types of soils, including three different silt loam layers and two different loam layers, were used in this study. The five soil layers were entitled as Silt loam 1, Silt loam 2, Silt loam 3, Loam 1 and Loam 2, respectively (Fig. 1). The soil materials were obtained from a soil profile in Tuanhe Farm, Daxing District of Beijing, China. Soil particle-size distribution was measured with Laser Particle Size Analyzer (Mastersizer 2000, Malvern Co., England). Soil bulk density was determined from the volume–mass relationship for each soil layer. Soil physical properties are shown in Table 1.

The distribution of the five soil layers is shown in Fig. 1. The corresponding depth of the interfaces between adjacent soil layers were 100, 120, 150 and 180 cm, respectively. Below the last soil layer, a depth of 5 cm pea-grave was filled for filtering. At the bottom of the column, there was a discharge chamber with length of 15 cm for drainage. A plastic perforated plate was used to separate the gravel filter and chamber (Fig. 1).

Table 1
Physical properties of soil layers used in this experiment.

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	Bulk density (g/cm^3)	θ_i[a] (cm^3/cm^3)
0–100	24.76	59.65	15.59	Silt loam	1.40	0.16
100–120	39.42	48.49	12.09	Loam	1.37	0.14
120–150	23.89	61.77	14.34	Silt loam	1.46	0.16
150–180	28.51	48.02	23.47	Loam	1.50	0.19
180–300	33.07	55.95	10.98	Silt loam	1.50	0.13

[a] θ_i is initial water content of soil layers.

After being mixed thoroughly and sieved through a 2 mm screen, the air-dried soils were compacted into the column in 5 cm increments with the targeted bulk density and initial water content (Table 1). The surface of each soil layer was corrugated into roughness before the next compacting. During the compacting process, nineteen tensiometers were installed at 10, 20, 30, 40, 50, 60, 80, 100, 110, 120, 130, 150, 160, 180, 200, 220, 240, 270 and 290 cm below the soil surface to measure the soil water pressure head (Fig. 1).

The infiltration experiment was conducted under ponding condition with a constant head of 7.5 cm. The experiment terminated when the wetting front reached the bottom of the last soil layer. The duration of the infiltration experiment was 4408 min. During the experiment, the water table of Mariotte bottle was measured to calculate the cumulative infiltration and infiltration rate. The depth of wetting front was also observed to calculate the movement velocity of wetting front. The soil water pressure head was measured to study water content distribution in the soil column. The infiltration experiment was carried out at 24 ± 1 °C. The evaporation relevant to the infiltration was so small that it could be neglected.

2.2. Unsaturated hydraulic properties of the soil profile

The soil water retention curves were measured with pressure-plate method. The measured results were fitted to the retention curve equations proposed by van Genuchten (1980) and Brooks and Corey (1964) with the RETC code developed by van Genuchten et al. (1991). The equation of van Genuchten model is described as (van Genuchten, 1980):

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = (1+|\alpha h|^n)^{-m} \quad h>0 \tag{1}$$

$$\theta = \theta_s \quad h \le 0 \tag{2}$$

where h is the soil water pressure head (cm), θ is the water content (cm^3/cm^3), θ_r and θ_s are the residual and saturated water contents (cm^3/cm^3), respectively, α, m and n are empirical parameters and $m=1-1/n$.

The equation of Brooks–Corey model is (Brooks and Corey, 1964):

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = \left(\frac{h_a}{h}\right)^{\lambda} = \left(\frac{1}{\alpha' h}\right)^{\lambda} \quad \alpha' h > 1 \tag{3}$$

$$\theta = \theta_s \quad \alpha' h \le 1 \tag{4}$$

where α' is an empirical parameter (1/cm) and it is the reciprocal of h_a, h_a is often referred to as the air entry value (cm), and λ is the pore-size distribution parameter affecting the slope of the retention function.

The fitting results indicated that the measured soil water retention curves were well described by the van Genuchten model. In this case, the unsaturated hydraulic conductivity of each soil layer can be expressed as (van Genuchten et al., 1991):

$$K(h) = \frac{K_s\{1-(\alpha h)^{mn}[1+(\alpha h)^n]^{-m}\}^2}{[1+(\alpha h)^n]^{ml}} \tag{5}$$

where K_s is the saturated hydraulic conductivity and l is an empirical parameter found to be equal to 0.5 for most soils. The corresponding soil hydraulic parameters of each layer are shown in Table 2. The air entry value h_a was obtained from Brooks–Corey model (Table 2).

2.3. Traditional Green–Ampt model

The Green–Ampt model was originally derived to analyze the ponding infiltration into uniform soil columns (Green and Ampt, 1911). The Green–Ampt model assumed that water flow in the saturated zone was caused by constant soil water suction at the wetting front and gravity of soil water. Water movement in the unsaturated zone was controlled by matric suction effects. Applying Darcy's law to the saturated zone, the infiltration rate can be expressed as (Green and Ampt, 1911):

$$i = K_s\frac{Z_f+H_0+S_f}{Z_f} = K_s\left(1+\frac{H_0+S_f}{Z_f}\right) \tag{6}$$

where i is the infiltration rate (cm/min), K_s is the hydraulic conductivity of upper saturated soil (cm/min), Z_f is the wetting front depth (cm), S_f is the wetting front suction head (cm), and H_0 is the depth of ponding water (cm).

To describe infiltration into non-uniform soils, some extended forms of the original Green–Ampt model have been proposed. For example, Han et al. (2001) applied the Green–Ampt model to account for infiltration into layered soils. The infiltration rate for layered soils was given by (Han et al., 2001):

$$i = \overline{K_s}\frac{Z_f+H_0+S_f}{Z_f} \tag{7}$$

The cumulative infiltration was described as (Han et al., 2001):

$$I = \sum_{j=1}^{M} D_j(\theta_{s,j}-\theta_{k,j}) + \left(Z_f - \sum_{j=1}^{M} D_j\right)(\theta_{s,M+1}-\theta_{k,M+1}) \tag{8}$$

The wetting front versus time was expressed in the following form (Han et al., 2001):

$$t-t_M=\frac{\theta_{s,M+1}-\theta_{k,M+1}}{\overline{K_s}}\left[(Z_f-z)-(S_f+H_0)\ln\left(\frac{Z_f+S_f+H_0}{z+S_f+H_0}\right)\right] \tag{9}$$

where D is the thickness of soil layer (cm), θ is the water content (cm^3/cm^3), t is the infiltration time (min), and z is the soil depth (cm). t_M is the time when the wetting front arrives at the lower boundary of the Mth layer (min). The subscripts k, s, j, M are referred to as initial state, saturated state, soil layer number and saturated layer number, respectively. $\overline{K_s}$ is the average saturated hydraulic conductivity of soil layers (Han et al., 2001):

$$\overline{K_s} = \frac{\sum_{j=1}^{M+1} D_j}{\sum_{j=1}^{M+1} D_j/K_{s,j}} \tag{10}$$

In the traditional Green–Ampt model, $K_{s,j}$ is referred to as the saturated hydraulic conductivity of jth layer. The suction head at wetting front S_f can be determined by the methods developed

Table 2
Soil hydraulic parameters obtained from RETC code for the soil layers.

Soil depth (cm)	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (1/cm)	n	m	l	K_s (cm/min)	α' (1/cm)
0–100	0.06	0.50	0.0111	1.2968	0.2289	0.5	0.01463	0.0095
100–120	0.08	0.51	0.0105	1.5465	0.3534	0.5	0.01924	0.0193
120–150	0.12	0.46	0.0069	1.5035	0.3349	0.5	0.01256	0.0093
150–180	0.14	0.50	0.0086	1.6109	0.3792	0.5	0.00505	0.0167
180–300	0.08	0.49	0.0054	1.5090	0.3373	0.5	0.01330	0.0068

by Bouwer (1969) and Neuman (1976). Bouwer (1969) suggested that:

$$S_{f\,\text{Bouwer}} = h_a/2 \tag{11}$$

where h_a is the air entry value, which can be determined from the equation of Brooks–Corey retention curve (Eq. (3)).

Subsequently, Neuman (1976) provided some theoretical justification for defining S_f as:

$$S_{f\,\text{Neuman}} = \int_0^{s_k} K_r ds \tag{12}$$

$$K_r = \frac{K(s)}{K_s} \tag{13}$$

where s is the soil suction (cm), s_k is the suction at initial water content (cm), K_r is the relative hydraulic conductivity, and $K(s)$ is the unsaturated hydraulic conductivity determined by Eq. (5).

2.4. Modified Green–Ampt model

According to the traditional Green–Ampt model, the hydraulic conductivity for wetted zone above the wetting front was considered as the saturated hydraulic conductivity, namely K_s. However, Bouwer (1966) and Hammecker et al. (2003) pointed out that because of entrapped air, the soil pores in saturated zone cannot be fully filled with water. Therefore, the actual hydraulic conductivity of saturated zone should be taken as the hydraulic conductivity at residual air saturation (K_0). K_0 should be somewhat less than K_s. Bouwer's (1966) suggestion was that $K_0 = 0.5K_s$.

In this study, a saturation coefficient S_e ($0 < S_e < 1$) was introduced to determine the proportion between K_0 and K_s. This coefficient had sound physical meaning, and it reflected the viscous resistance of air flow and saturation degree of soil pores in wetted zone. S_e was assumed to be identical for every soil layer, and it was equal to the ratio between measured moisture volume and total saturated moisture volume of the wetted zone. S_e can be expressed by the following equation:

$$S_e = \frac{S_m}{S_s} = \frac{I_t + S_0}{S_s} \tag{14}$$

where S_m is the measured moisture volume of the wetted zone, I_t is the measured total cumulative infiltration (cm), S_0 and S_s are the total initial moisture volume and total saturated moisture volume of the wetted zone (cm), respectively. S_0 and S_s were calculated by the initial water content (θ_i) and saturated water content (θ_s) of each soil layer, respectively. Thus, in the modified Green–Ampt model, the actual hydraulic conductivity of saturated zone (K_0) can be described as $K_0 = S_e K_s$, and soil water content of saturated zone (θ_0) can be defined as $\theta_0 = S_e \theta_s$. Subsequently, the parameters θ_0 and K_0 instead of θ_s and K_s respectively, were substituted to Eqs. (10), (7)–(9) to determine the infiltration rate, the cumulative infiltration and the depth of wetting front. In the modified Green–Ampt model, S_f was also obtained from the methods developed by Bouwer (1969) and Neuman (1976).

2.5. Theory of HYDRUS-1D

The HYDRUS-1D code was based on the one-dimensional Richards equation to simulate water movement in variably saturated media, and the equation was solved by numerical method (Šimůnek et al., 2005). The basic water movement equation was described as:

$$\frac{\partial\theta(h,t)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] \tag{15}$$

where h is the soil water pressure head, θ is the volumetric water content, t is time, z is the vertical coordinate with the origin at the soil surface (positive upward), and $K(h)$ is the unsaturated hydraulic conductivity determined by Eq. (5).

For the experiment studied, the initial condition and upper boundary condition were:

$$h(z,0) = h_i(z) \tag{16}$$

$$h(0,t) = h_0 \tag{17}$$

where $h_i(z)$ is the initial soil water pressure head through the soil column, and h_0 is the soil water potential at soil surface.

The free drainage was to be considered as lower boundary condition:

$$\frac{\partial h}{\partial z} = 0 \tag{18}$$

The traditional Green–Ampt model, HYDRUS-1D and modified Green–Ampt model were applied to simulate the infiltration rate, the cumulative infiltration and the depth of wetting front. In the following analysis, the "Neuman method" and "Bouwer method" indicated that the suction head at wetting front (S_f) in the Green–Ampt model were determined by the method developed by Neuman (1976) and Bouwer (1969), respectively. To compare all the models considered, the root mean square error (RMSE) was used as a criteria to reflect the goodness of simulation, which can be expressed as:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2} \tag{19}$$

where N is the total number of observations, O_i and P_i are the observed and predicted values of the ith observation, respectively.

3. Results and discussion

3.1. Analysis of experimental data

Fig. 2 shows the measured infiltration rate and cumulative infiltration in the large soil column. From Fig. 2, it can be found that the infiltration rate decreased rapidly at the beginning, and approached a stable value gradually after 400 min. The steady infiltration rate was about 0.015 cm/min. The measured total cumulative infiltration was 73.05 cm. As shown in Fig. 2, the cumulative infiltration increased gradually through the whole infiltration process, and it

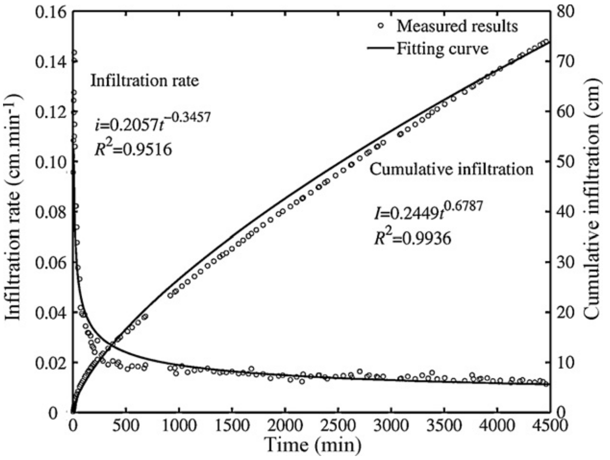

Fig. 2. Measured infiltration rate and cumulative infiltration through the whole infiltration process. The fitted results with power law function are also shown.

can be expressed as a linear function of time at the later infiltration stage.

Fig. 3 shows the advancing rate of wetting front. The wetting front reached the four interfaces between adjacent soil layers (as shown in Fig. 1) at 793, 1048, 1539 and 1917 min, respectively. The advancing rate of wetting front had a decrease trend with time and approached a stable value, as evident from Fig. 3. Moreover, the movement velocity of wetting front changed greatly at the soil layer interfaces. This result was due to the differences of soil physical properties between adjacent soil layers, such as soil structure, soil texture and initial water content.

It is interesting to note that the infiltration rate, the cumulative infiltration, and the movement velocity of wetting front, all can be well fitted by power law functions, as shown in Figs. 2 and 3. All the coefficients of correlation (R^2) are larger than 0.95. However, the power law function is only an empirical model to describe infiltration process. It may be only suitable for describing infiltration process in this specific infiltration experiment. For other infiltration cases, the power law function may not be available or the fitted parameters may change. Therefore, for more robustly physical and popular application, the mathematical models are sorely needed to describe the infiltration process.

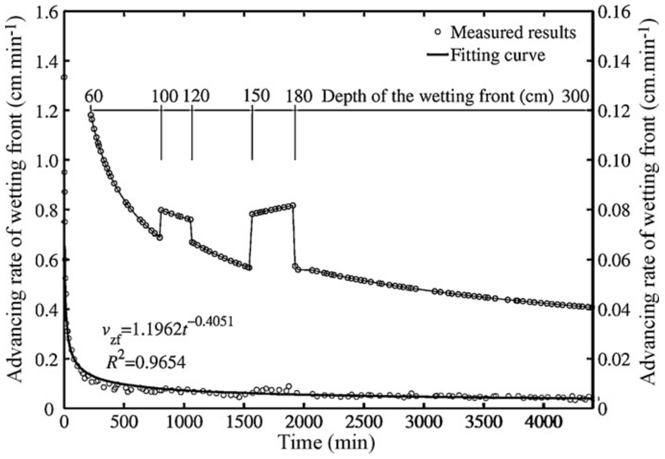

Fig. 3. Measured advancing rate of the wetting front through the soil column. Left *y*-axis represents advancing rate of wetting front moving from 0 to 300 cm. Right *y*-axis represents advancing rate of wetting front moving from 60 to 300 cm.

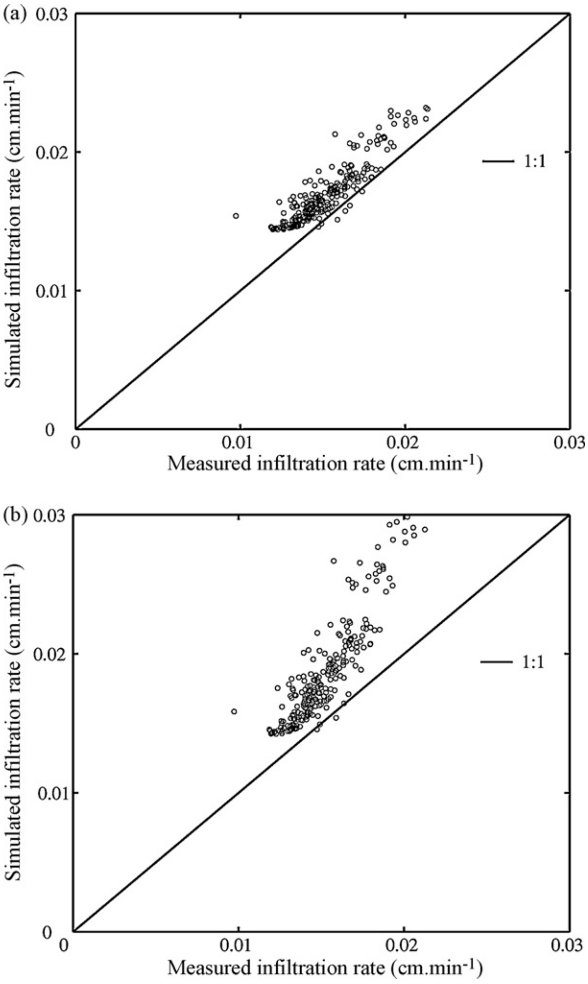

Fig. 4. Comparison of simulated infiltration rate by the traditional Green–Ampt model with measured result. The wetting front suction head (S_f) in the traditional Green–Ampt model was determined by (a) Neuman method, and (b) Bouwer method. The line represents the potential 1:1 relationship between the data sets.

3.2. Comparison of modified Green–Ampt model with traditional Green–Ampt model and HYDRUS-1D

In this experiment, the measured total cumulative infiltration (I_t) was 73.05 cm. The measured total initial moisture volume (S_0) and saturated moisture volume (S_s) in the soil column were 44.9 and 147.8 cm, respectively. In terms of Eq. (11), the value of saturated coefficient (S_e) introduced in the modified Green–Ampt model was 0.8. Hence, the effective water content (θ_0) and hydraulic conductivity (K_0) used in the modified Green–Ampt model were $0.8\theta_s$ and $0.8K_s$, respectively. It should be noted that in the traditional Green–Ampt model and HYDRUS-1D, the water content and hydraulic conductivity of upper saturated zone were saturated water content (θ_s) and saturated hydraulic conductivity (K_s), respectively. The simulated results of these three models are shown in Figs. 4–8 and the corresponding RMSE values are listed in Table 3.

3.2.1. Infiltration rate

Fig. 4 shows the comparison of observed infiltration rates with those simulated by traditional Green–Ampt model. The simulation results of traditional Green–Ampt model with Neuman method are somewhat larger than measured results (Fig. 4a). For traditional Green–Ampt model with Bouwer method, there are pronounced discrepancies between measured and simulated infiltration rates, as evident from Fig. 4b. The better performance of Neuman method

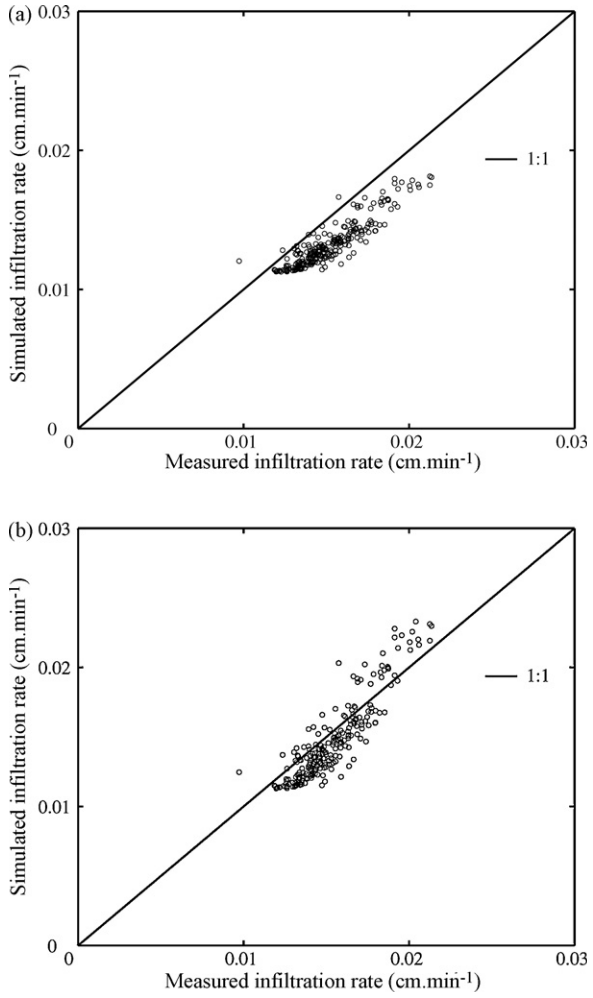

Fig. 5. Comparison of simulated infiltration rate by the modified Green–Ampt model with measured result. The wetting front suction head (S_f) in the modified Green–Ampt model was determined by (a) Neuman method, and (b) Bouwer method. The line represents the potential 1:1 relationship between the data sets.

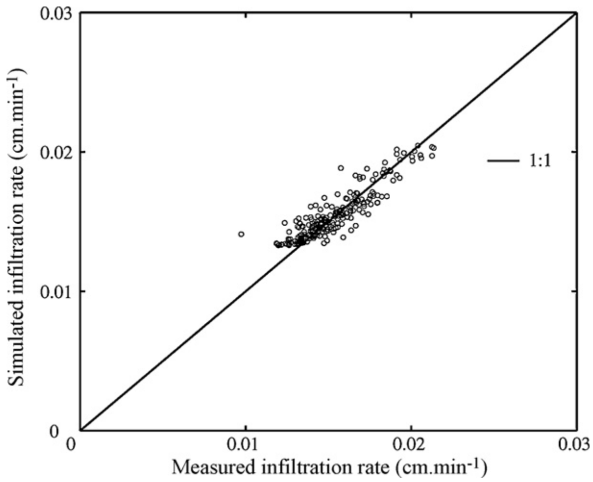

Fig. 6. Comparison of simulated infiltration rate by HYDRUS-1D with measured result. The line represents the potential 1:1 relationship between the data sets.

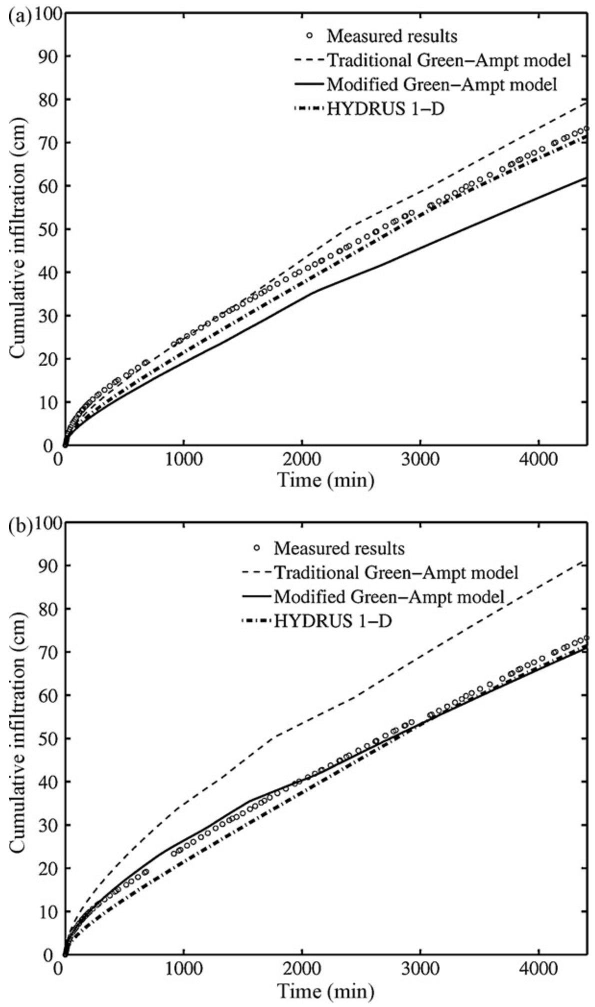

Fig. 7. Comparison of cumulative infiltration simulated by the traditional Green–Ampt model, modified Green–Ampt model and HYDRUS-1D. The wetting front suction head (S_f) in the Green–Ampt models was determined by (a) Neuman method, and (b) Bouwer method.

for traditional Green–Ampt model can be also indicated by its smaller RMSE value than that of Bouwer method (Table 3).

As shown in Fig. 5, the infiltration rates simulated by modified Green–Ampt model are well correlated with the measured data, for both the Neuman and Bouwer method. The modified Green–Ampt model better represents the measured infiltration rate than traditional Green–Ampt model, as evident from Figs. 4 and 5. This result can be also indicated by the smaller RMSE values of modified Green–Ampt model than those of traditional Green–Ampt model (Table 3). Fig. 6 shows the plots of simulated infiltration rates by HYDRUS-1D versus observed results. It can be found that HYDRUS-1D can describe the infiltration rates adequately as the modified Green–Ampt model.

3.2.2. *Cumulative infiltration*

Fig. 7a shows the cumulative infiltration simulated by the traditional and modified Green–Ampt model with Neuman method, and HYDRUS-1D. It can be found that the simulated results by traditional Green–Ampt model are somewhat larger than the measured results, especially at the later stage of infiltration. The modified Green–Ampt model provides smaller cumulative infiltration than the observed data. Compared to the traditional and modified Green–Ampt model, the simulation results of HYDRUS-1D are very close to the observed results (Fig. 7a).

Table 3
The root mean square error (RMSE) values for simulation results of traditional Green–Ampt model, modified Green–Ampt model and HYDRUS-1D.

	Traditional Green–Ampt model		Modified Green–Ampt model		HYDRUS-1D
	Neuman method	Bouwer method	Neuman method	Bouwer method	
Infiltration rate (cm/min)	2.56E−3	5.27E−3	2.39E−3	2.01E−3	1.01E−3
Cumulative infiltration (cm)	3.02	11.27	6.91	1.28	2.48
Wetting front depth (cm)	47.28	19.32	35.89	8.29	57.17

An inspection of Fig. 7b shows that the cumulative infiltration simulated by modified Green–Ampt model with Bouwer method is in perfect agreement with the measured data. The performance of modified Green–Ampt model with Bouwer method is better than that of HYDRUS-1D and traditional Green–Ampt model with Bouwer method, as evident from Fig. 7b. The RMSE value of modified Green–Ampt model with Bouwer method (1.28 cm) is much smaller than that of HYDRUS-1D (2.48 cm) and traditional Green–Ampt model with Bouwer method (11.27 cm).

3.2.3. Wetting front depth

Fig. 8 shows the comparison of wetting front depth simulated by the traditional and modified Green–Ampt model, and HYDRUS-1D. It can be found that the simulated wetting front depths of traditional Green–Ampt model and HYDRUS-1D diverge greatly from observed results. The modified Green–Ampt model better describes the depths of wetting front than the other two models, as evident from Fig. 8. Furthermore, the wetting front depths simulated by modified Green–Ampt model with Bouwer method are in best agreement with measured results, which can be verified by the smallest RMSE value of 8.29 cm.

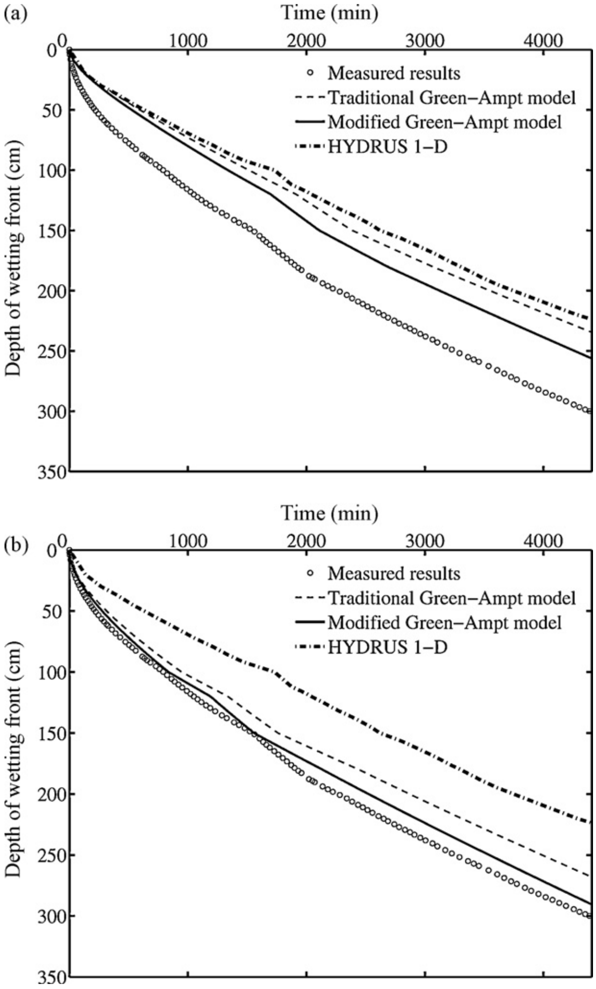

Fig. 8. Comparison of wetting front depth simulated by the traditional Green–Ampt model, modified Green–Ampt model and HYDRUS-1D. The wetting front suction head (S_f) in the Green–Ampt models was determined by (a) Neuman method, and (b) Bouwer method.

It is very interesting to note that the HYDRUS-1D code severely underestimates the advancing depth of wetting front (Fig. 8). Particularly at the termination of infiltration experiment, the measured depth of wetting front was 300 cm, while the corresponding wetting front depth simulated with HYDRUS-1D was only 224 cm. The problem of HYDRUS-1D is due to that it neglects the effect of air flow on water infiltration and it assumes that the soil above wetting front is fully saturated. However, as a result of entrapped air bubbles left in soil pores, the water content of wetted zone can not reach saturated water content (θ_s) and the actual infiltration capacity is lower than saturated hydraulic conductivity (K_s) (Bouwer, 1966; Hammecker et al., 2003). This means that HYDRUS-1D overestimates the capacity of wetted zone to hold water. According to the law of mass conservation, under the condition of equivalent cumulative infiltration, the larger water holding capacity that the soil has, the smaller advancing depth that the wetting front can move. Therefore, the advancing depth of wetting front simulated by HYDRUS-1D lags behind the measured results. There are two ways to account for the problem of HYDRUS-1D. First, the saturated hydraulic conductivity K_s in Eq. (5) should be replaced by hydraulic conductivity at residual air saturation K_0 to determine the unsaturated hydraulic conductivity $K(h)$ used in the Richards equation (Eq. (15)). Second, the presence of air should be taken in to account to quantify the flow of water into soil. The two-phase (gaseous and liquid phase) flow model should be incorporated into HYDRUS-1D.

4. Summary and conclusions

This study presented a modified Green–Ampt model to predict infiltration through layered soils. An infiltration experiment was conducted in a 300-cm long and five-layered soil column to test validity of the proposed model. In the modified Green–Ampt model, a saturation coefficient (S_e) was introduced to account for air entrapment in upper wetted zone. The water content and hydraulic conductivity of the upper wetted zone were equal to $S_e\theta_s$ and S_eK_s, respectively, instead of θ_s and K_s used in traditional Green–Ampt model. The saturation coefficient was determined by the ratio between measured moisture volume and total saturated moisture volume of the wetted zone. The wetting front suction head in Green–Ampt model was determined with the approaches developed by Bouwer (1969) and Neuman (1976). The numerical model HYDRUS-1D was also used to describe infiltration in the large layered soil column for comparison.

The experimental data showed that the infiltration rate decreased through the layered soil column as the soil compactness increased with depth. In addition, the infiltration rate did not change significantly when the wetting front moved across the interface between adjacent soil layers. The fitting of experimental data indicated that the measured infiltration rate, the accumulative infiltration, and the velocity of the wetting front were all well described by power law functions of the infiltration time.

The modeling results of the infiltration rate, the accumulative infiltration and the depth of the wetting front by traditional Green–Ampt model were apart from measured results. The infiltration rate and the accumulative infiltration simulated by HYDRUS-1D were in good agreement with the observed results. However, the HYDRUS-1D was difficult to track the movement of wetting front as it underestimated the wetting front depth. Comparing to the traditional Green–Ampt model, the modified Green–Ampt model better captured the infiltration process in the large layered soil column when the wetting front suction head was determined by Bouwer method (1969). Furthermore, the modified Green–Ampt model could better describe the advancing depth of wetting front than HYDRUS-1D. Therefore, it appears that the modified Green–Ampt model can be used as a highly effective and practical method to estimate water infiltration in layered soils, and the introduced saturation coefficient robustly reflects the effect of air entrapment on water infiltration.

Conflict of interest

No conflict of interest.

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