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One—Dimensional Seepage of Unsaturated Soil Based on Soil—Water Characteristic Curve

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Abstract: The uneven pore water distribution in unsaturated soil will cause water movement, change the hydraulic and mechanical characteristics of soil, and then cause soil damage. Therefore, it is important to study the hydraulic characteristics of unsaturated soil. In this paper, the law of conservation of mass and Darcy's law were used to analyze the unit soil after seepage to obtain a continuous equation. Combined with the soil-water characteristic curve (SWCC), the effect of matric suction and permeability coefficient of unsaturated soil on infiltration rate is substituted into the equation. Through the analysis of pore water stress of the unit soil, the function of the unsaturated permeability coefficient with the effective saturation degree is obtained, and the theoretical formula of the one-dimensional infiltration rate of unsaturated soil is derived. Compared with other models, this formula has fewer parameters and is easy to use.

Keywords: soil-water characteristic curve; permeability coefficient; seepage; water content

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Citation: Shao, L.; Wu, S.; Guo, X.; Wen, T. One—Dimensional Seepage of Unsaturated Soil Based on Soil—Water Characteristic Curve. *Processes* **2022**, *10*, 2564. https://doi.org/10.3390/pr10122564

Academic Editors: Chenju Liang and Carlos Sierra Fernández

Received: 27 October 2022
Accepted: 21 November 2022
Published: 2 December 2022

1. Introduction

Most of geotechnical engineering designs and calculations use saturated soil mechanics theory [1,2], which may be conservative for unsaturated soils and sometimes may even lead to unreasonable results [3–5]. The hydraulic properties of unsaturated soil include the permeability coefficient function and the SWCC. The relationship between water content and matric suction at various points in the soil follows the SWCC when the water in the soil is in a static equilibrium state. However, water content in the soil is often irregular and unevenly distributed due to rain, snow, evaporation, and other factors. At this time, the water will move under the action of the water potential gradient and tend to the static equilibrium state. This paper will discuss the solution method of the one-dimensional seepage problem for unsaturated soil.

The Green-Ampt model [6] is the most classical model for studying infiltration, as follows:

$$I = k_s\,[1 + (\theta_s - \theta_i)s_t/I] \tag{1}$$

$$k_s t = I - s_t\,(\theta_s - \theta_i)\ln\,[1 + I/s_t\,(\theta_s - \theta_i)] \tag{2}$$

$$I = (\theta_s - \theta_i)\,z_t \tag{3}$$

where k_s is the saturated permeability coefficient, s_t is the air entry value, θ_s is the saturated volume moisture content of soil, z_t is the infiltration depth, I is the calculate infiltration volume, and i is the infiltration rate. The calculation of the Green-Ampt model is deeply affected by the air entry value, which is difficult to accurately measure.

Many scholars have revised the Green-Ampt model to gain a more precise solution. Bouwer [7] proposed that the hydraulic conductivity k_0 = 0.5 k_s and the air entry value of soil should be 0.5 s_t. Mein and Larson [8] proposed to use the weighted average value of soil water suction s as s_t, that is $s_t = \int_0^1 s\mathrm{d}k_r$ in which $k_r = k(\mathrm{S})/k_s$ is the relative hydraulic conductivity.

The equation proposed by Richards [9] is most commonly used to describe the unsaturated soil rainfall infiltration problem. But Richard's equation can only be applied to a limited number of cases involving homogeneous soils, simplified initial and boundary conditions [10], and simple constitutive relationships that detail unsaturated hydraulic properties, mainly water content and permeability change with soil suction. Gardner's exponential model [11] which relates hydraulic conductivity with the pressure head, as shown in Equation (4), is also used for linearization.

$$k_u = k_s e^{-\alpha(u_a - u_w)} \tag{4}$$

where k_u is the unsaturated permeability coefficient (m/s), α is the inverse of air-entry pressure (kPa^{-1}), u_a is the pore air pressure (kPa), u_w ia the pore water pressure (kPa), and $(u_a - u_w)$ is the matric suction (kPa).

Approximate solutions are generally obtained with the help of numerical methods, since it is very difficult to obtain the analytical solution of the Equation [12]. The commonly used numerical methods that have high accuracy are meshless methods [13] and finite difference methods [14], etc. In addition, Li et al. [15] conducted water loss experiments on unsaturated soils under different air pressures by using the axis translation technique. They also established the pore pressure dissipation equation for triaxial specimens at constant air pressure. Dolejsi et al. [16] proposed the adaptive high-order discontinuous Galerkin method to solve the seepage problem of unsaturated soils. Garcia et al. [17] proposed a model with a multiphase coupled elasto-viscoplastic finite element analysis formulation to describe the rainfall infiltration process into an one-dimensional soil column based on the theory of porous media, which proved that parameters of α, m and n' in the van Genuchten–Mualem model have significant effect on the one-dimensional infiltration process. The van Genuchten–Mualem model [18] is useful for multiple layered unsaturated soils, in which the steady states for soils were reached faster with a smaller value for α, as well as a larger of m and n, as shown in Equation (5). However, it is difficult to obtain analytical solutions because of the large number of parameters.

$$k_u = k_s \frac{\left\{1 - (\alpha\psi)^{n-1}\left[1 + (\alpha\psi)^n\right]^{-m}\right\}^2}{\left[1 + (\alpha\psi)^n\right]^{m/2}} \tag{5}$$

where, ψ is matric suction, and α, m and n are fitting parameters of the soil-water characteristic curve.

Most of the models and formulas proposed by scholars obtain an analytical solution, without considering the influence of moisture content and matric suction on the permeability coefficient, and often have more fitting parameters and are inconvenient to use. In this paper, a method for calculating the unsaturated one-dimensional vertical infiltration rate is proposed based on the SWCC. Firstly, the mass conservation analysis of the element body is performed to obtain the continuity equation. Secondly, the permeability coefficient is introduced into the continuous equation by Darcy's law. Finally, the expression of the infiltration rate containing water content can be obtained by using the permeability coefficient function.

2. Experimental Tests of SWCC

It is necessary to measure the SWCC, saturation permeability coefficient, and porosity ratio of the soil in relation to the soil-water force coefficient (η), while using a theoretical formula based on the SWCC derivation.

The SWCC of the three soils mentioned in this paper ere measured by a combined tester of the unsaturated soil-water characteristic curve and water conductivity [19–22], as shown in Figure 1. The sample is made with a special ring knife, the soil sample is 20 mm high and 54.7 mm in diameter, and there are small holes with breathable and impermeable film in the middle of the ring knife, and there are clay plates above and below the soil sample. Before the experiment, the soil sample was fully saturated by vacuuming for at least an hour and then put into water for more than 24 h. During the test, the multi-step overflow method was used to apply air pressure step by step. With the increase of air pressure, pore water will be discharged, and the matric suction of the soil sample will be increased. We recorded the water displacement every hour. When the difference between the water displacement for two consecutive hours is less than 0.001 mL, we think that the matric suction and air pressure are in equilibrium, and then apply a new level of air pressure. The pore water was discharged from the upper and lower clay plates to the balance through the small hole in the middle. Because the test takes a long time, an evaporation compensation balance is set up, which reduces the experimental error caused by evaporation [23].

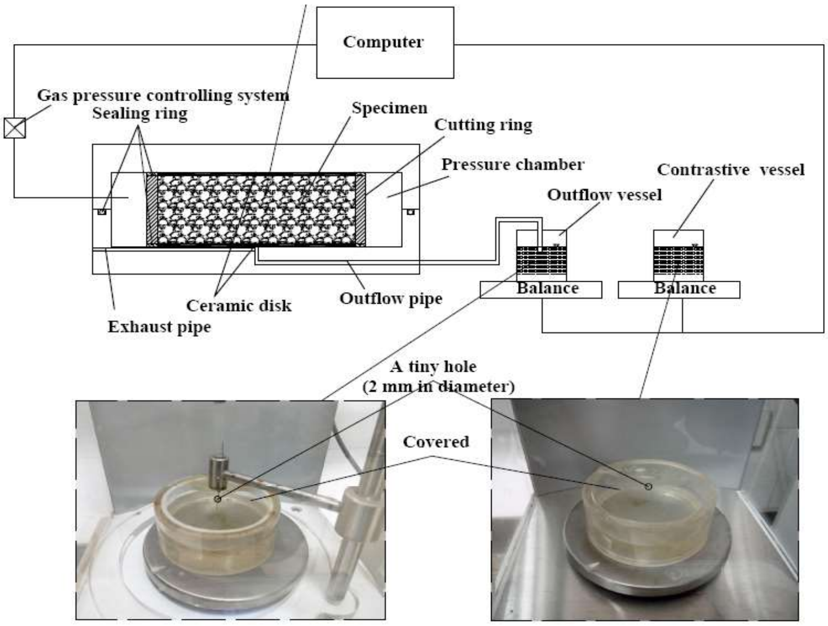


Figure 1. Schematic diagram of the instrument.

3. Numerical Analysis

3.1. Soil Water Characteristic Curve

The SWCC describes the relationship curve between matric suction and water content of pore water under hydrostatic equilibrium. When the gravity of pore water in a unit is balanced with matric suction, this point will be in a stable state of hydrostatic equilibrium and will fall on the SWCC. Under the condition of hydrostatic equilibrium, the shape of the relationship curve between water content and soil buried depth is similar to that of the SWCC (Figure 2). Many symbols are involved in the formula derivation, as shown in the Table 1.

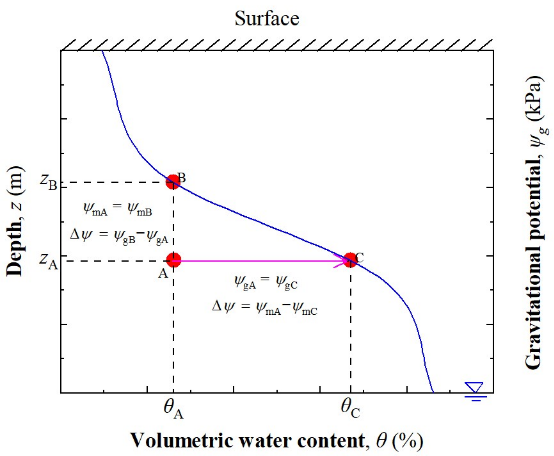


Figure 2. Schematic diagram of soil water characteristic curve.

Table 1. List of main symbols.

Symbol	Significance	Unit
k_u	Unsaturated permeability coefficient	m/s
k_s	Saturated permeability coefficient	m/s
v	Seepage velocity	m/s
u_a	Pore gas pressure	kPa
u_w	Pore water pressure	kPa
θ_w	Volumetric water content	1
θ_s	Saturated volume water content	1
t	Time	s
i	Hydraulic gradient	1
s_t	Air-entry value	kPa
z	Depth	m
ψ	Matric suction	kPa
n	Porosity	1
n_w	Water porosity	1
η	Soil-water force coefficient	1

In the equilibrium and stable state, the moisture content of unsaturated soil decreases with the increase of the distance to the groundwater level. Point A is in an unbalanced state, while point B and point C on the curve are in equilibrium. By analyzing the total potential energy of A, B, and C respectively, it can be found that:

$$\psi = \psi_g + \psi_m + \psi_t + \psi_s + \psi_p \tag{6}$$

while ψ is total potential, ψ_g is gravitational potential, ψ_m is matric potential, ψ_t is temperature potential, ψ_s is solute potential, ψ_p is pressure potential.

Gravitational potential at point A and point C is obviously equal, so the soil water potential driving point A in the unstable state to point C in the stable state is the matric potential difference between point A and point C. The matric potential of point C can be obtained directly from the SWCC and water content (Figure 1). But point A is in an unbalanced state and does not fall on the SWCC, therefore, its matric potential cannot be obtained directly. By analyzing the total potential energy difference between point A and point B:

$$\Delta\psi = z_A + \psi_m^A - z_B - \psi_m^B = -\Delta z \tag{7}$$

where ψ is the soil water potential, ψ_m is the matric potential and z is the gravity potential. $\Delta z = z - z_A$, therefore, the matric potentials of points A and B are equal. Point B is in a stable state, and the matric potential can be determined by SWCC and water content, so the potential energy which makes point A move to point C:

$$\Delta\psi = \Delta\psi_m = \psi_m^B - \psi_m^C \tag{8}$$

3.2. Mass Conservation Equation

Take the unit soil mass at point A for mass conservation analysis: Before and after percolation, the mass of the solid skeleton in the unit remains unchanged, the water content changes, and the amount of change in the total mass is equal to that in the mass of the pore water (Figure 3).

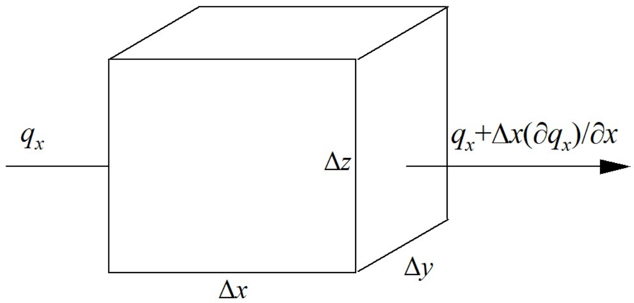


Figure 3. One-dimensional seepage of a unit body.

The mass of water within the soil is $\rho_w \Delta\theta \Delta x \Delta y \Delta z$. The solid phase skeleton Δx, Δy, and Δz within the cell is constant.

The continuity equation can be obtained:

$$\frac{\partial \rho_w \theta}{\partial t} = -\left(\frac{\partial \rho_w q_x}{\partial x} + \frac{\partial \rho_w q_y}{\partial y} + \frac{\partial \rho_w q_z}{\partial z} \right) \tag{9}$$

When soil water is considered incompressible, ρ_w is a constant, the equation of soil water flow in unsaturated soil can be obtained by Darcy's law:

$$\frac{\partial \theta}{\partial t} = \nabla[k(\theta)\nabla\psi] \tag{10}$$

where $k(\theta)$ is the unsaturated infiltration coefficient function. Considering a one-dimensional vertical flow and the isotropic soil layer, we can obtain:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(\theta) \frac{\partial \psi_m}{\partial z} \right] + \frac{\partial k(\theta)}{\partial z} \tag{11}$$

3.3. Unsaturated Permeability Function

It is assumed that the distribution of pore water in soil elements is uniform. Under assumed conditions that ignore the interaction force between pore water and pore gas, the pore water of the soil element is separately analyzed by force, as shown in Figure 4.

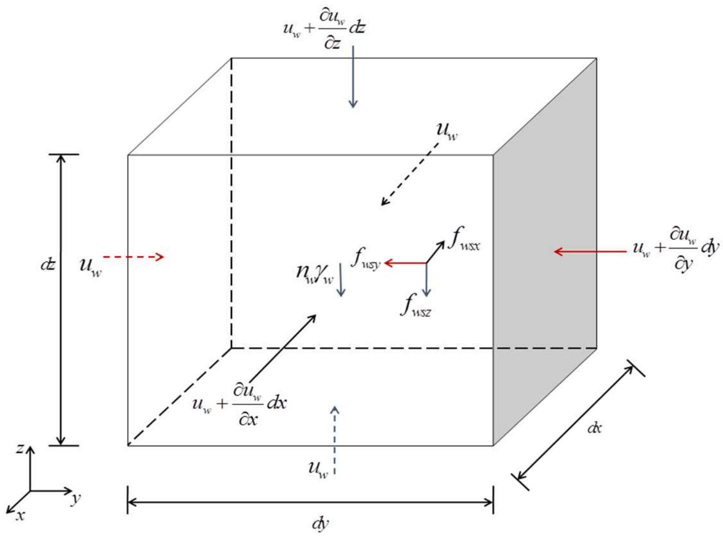


Figure 4. Equilibrium for pore-water phase of unsaturated soil.

Equilibrium differential equations for pore water in the excavation can be obtained:

$$n_w (u_w)_i + f_{swi} + X_{wi} = 0 \tag{12}$$

where, n_w is the porosity corresponding to the pore water of unsaturated soil, u_w is the pore water pressure, f_{swi} represents the interaction force between the soil skeleton and the pore water, and X_{wi} is the volume force acting on the pore water micro element.

Derived from the equilibrium differential equation for pore water in unsaturated soils:

$$n\gamma_w(h-z)_i + \eta\frac{v_i}{n} + X_{wi} = 0 \tag{13}$$

where the soil-water force coefficient η can be calculated indirectly according to the porosity and the permeability coefficient:

$$\eta = \frac{n^2\gamma_w}{k_s} \tag{14}$$

In the proposed permeation formula, the permeability coefficient can be expressed as a power function relationship of porosity:

$$\eta = \lambda n^{-\beta} \tag{15}$$

where λ and β are arguments to the power function, and can be obtained through the seepage experiment.

The functional expression of the permeability coefficient of unsaturated soils can be given by Equation (16), which is also used to solve Equation (11):

$$k(\theta) = k_s S^{1+\beta} \tag{16}$$

Combining Equation (11), we can obtain:

$$\frac{\partial\theta}{\partial t} = \alpha^2\frac{\partial^2\psi_m}{\partial\theta^2}k(\theta) + \alpha(1+\frac{\alpha\partial\psi_m}{\partial\theta})\frac{\partial k(\theta)}{\partial\theta} \tag{17}$$

$$k(\theta) = k_s S^{1+\beta} \tag{18}$$

$$\alpha = \frac{\partial\theta}{\partial z} \tag{19}$$

where α is the slope of the infiltration front. It is assumed that the volumetric water content of the soil changes linearly with depth when the water infiltrates (Figure 5).

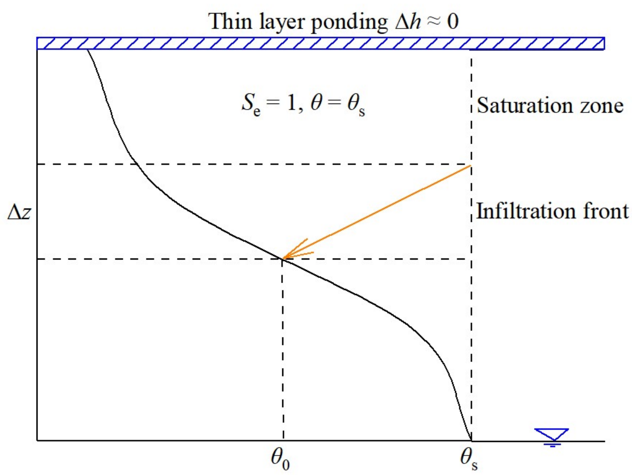


Figure 5. Schematic diagram of soil water infiltration.

4. Numerical Results and Discussion

In this paper, a kind of unconsolidated sand, Touchet silt loam soil, and microsilica are selected as examples to compare the calculation results based on the SWCC derivation formula and the classical model formulas (Green-Ampt model, Bouwer formula, van

Genuchten–Mualem model). We assume that the distribution of volumetric water content in the unsaturated area of soil with depth is as is shown as in (Figure 5). The calculation parameters and the SWCC of unconsolidated sand, Touchet silt loam soil, and microsilica were obtained (Tables 2 and 3, Figures 6–8), through infiltration experiments [16]. The change curves of the infiltration rate of unconsolidated sand, Touchet silt loam soil, and microsilica with the initial moisture content are shown in Figure 8.

Table 2. Soil properties and parameters.

Soils	k_s **(cm/h)**	β	θ_s	θ_r	s_t **(kPa)**
Sand	20	2.293	0.32	0.028	3
Silty loam	0.05	4.507	0.45	0.24	8
Microsilica	0.0392	7.351	0.52	-	32

Table 3. Fitting VG parameters of soil-water characteristic curves of three kinds of soils.

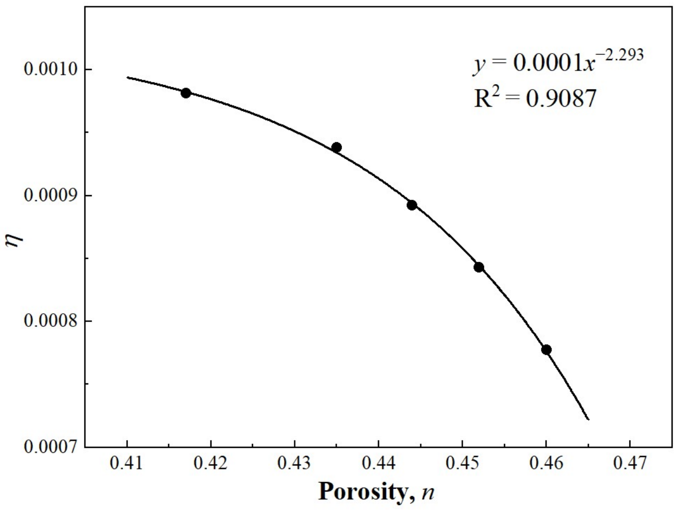
Soils	α	n	m
Sand	0.1757	1.6085	0.3783
Silty loam	0.1197	1.4836	0.326
Microsilica	0.0049	1.4733	0.3213

The SWCC has two inflection points: the air entry value and the residual moisture content. The air entry value refers to the value of the substrate suction force when the soil begins to drain significantly, and the residual water content refers to the corresponding moisture content when the soil is no longer drained. Due to poor water retention, the air entry value of unconsolidated sand is very small, while the air entry value of Touchet silt loam soil is greater than that of unconsolidated sand and less than microsilica. The air entry value of microsilica is generally large, and when the matric suction is large, the residual moisture content of clay can be achieved, so the SWCC of clay is difficult to obtain completely through experiments. The soil-water characteristic curve of microsilica in this paper was not fully measured because of the limited experimental conditions. The volumetric moisture content corresponding to the maximum matric suction (600 kPa) achieved in the experiment is 27%.

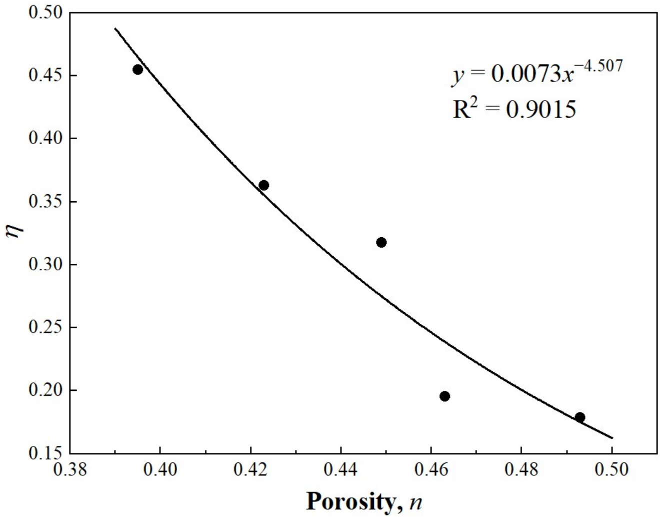
In general, the calculation result of the method proposed in this paper is the closest to that of the van Genuchten–Mualem model. The calculation result of the unconsolidated sand based on the formula derived from the SWCC is close to and slightly smaller than that of Bouwer's modified formula (Figure 9a); while the infiltration curve of Touchet silty loam is between those of the Green-Ampt model and Bouwer's modified formula (Figure 9b); the calculation results of microsilica based on the SWCC derivation formula are significantly higher than those of Bouwer's correction formula (Figure 9c).

The air entry value of the three soils is very different, among which the air entry value of unconsolidated sand is very small and often not more than 10 kPa, the Touchet silty loam contains more clay particles and has a higher air entry value, while the air entry value of microsilica is the largest. Half of the air entry value is used by Bouwer's modified formula, thus it is the reason that the calculation results of Touchet silty loam and microsilica based on the formula derived from the SWCC is higher than that of Bouwer's correction formula.

To sum up, the more cohesive particles in the soil, the greater the difference between the result based on the SWCC derivation formula and the calculation of Bouwer's modified formula. For geotechnical engineering, the greater the infiltration rate of the soil, the more dangerous the engineering structure, so that the advantage of the formula mentioned in this paper over Bouwer's formula is that, under reasonable consideration of the SWCC and matric suction, the calculation of the unsaturated infiltration rate is larger when the soil contains clay particles. At the same time, the calculation result of the Green-Ampt model is too conservative. Therefore, the formula derived from the SWCC provides a safer consideration for engineering.



(**a**)



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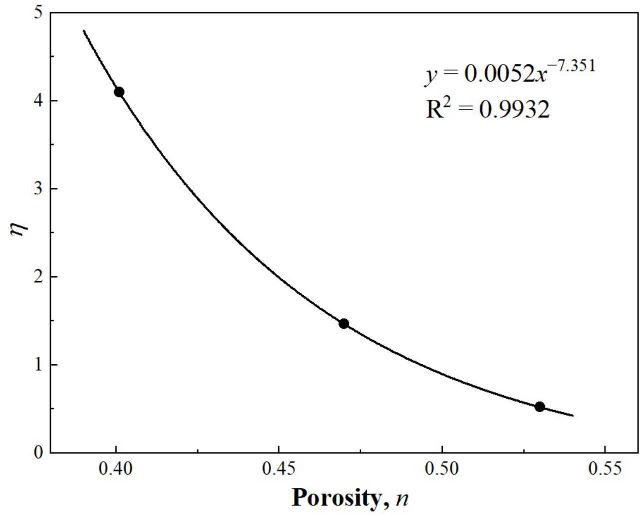


(**c**)

Figure 6. Relationship between porosity and soil-water force coefficient: (**a**) Unconsolidated sand; (**b**) Touchet silt loam; (**c**) microsilica.

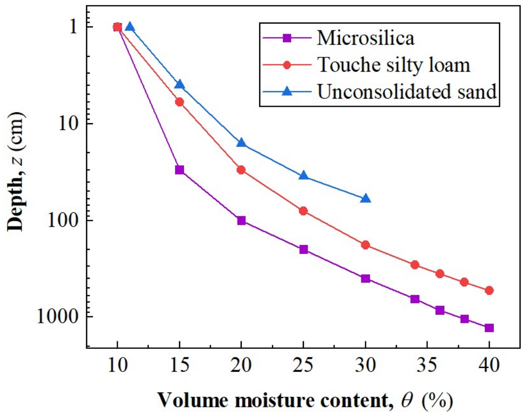


Figure 7. Relationship between volumetric moisture content and buried depth.

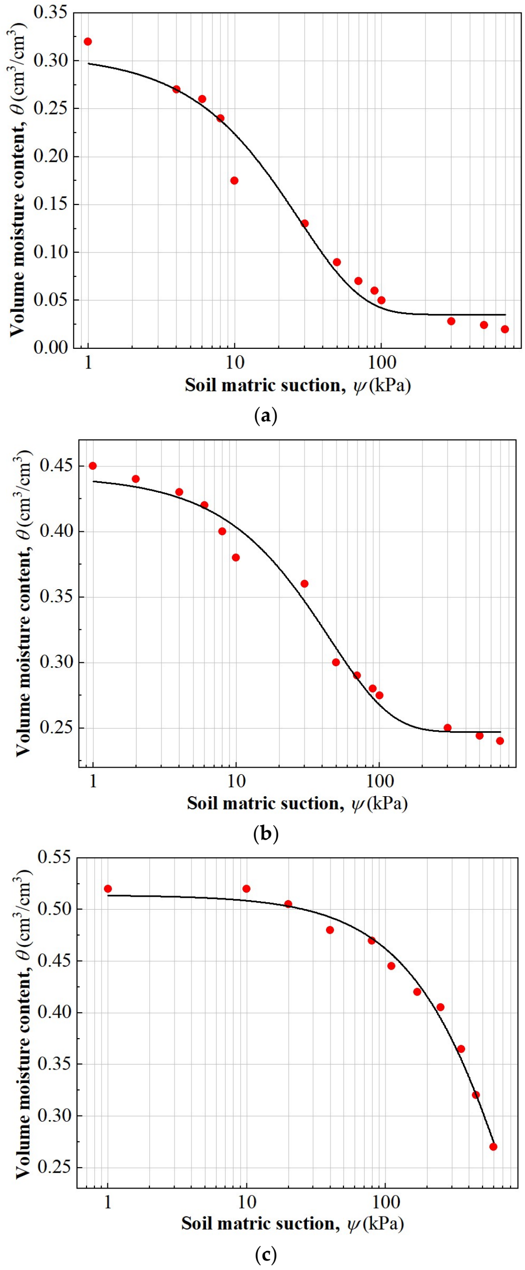
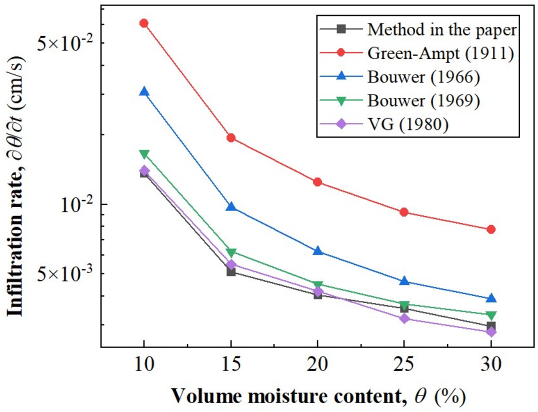
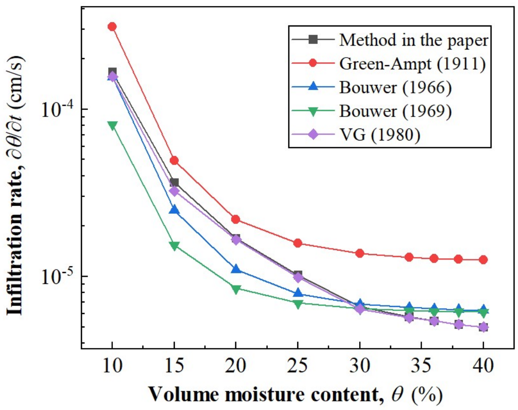


Figure 8. Soil water characteristic curve: (**a**) unconsolidated sand; (**b**) Touchet silty loam; (**c**) microsilica.



(**a**)



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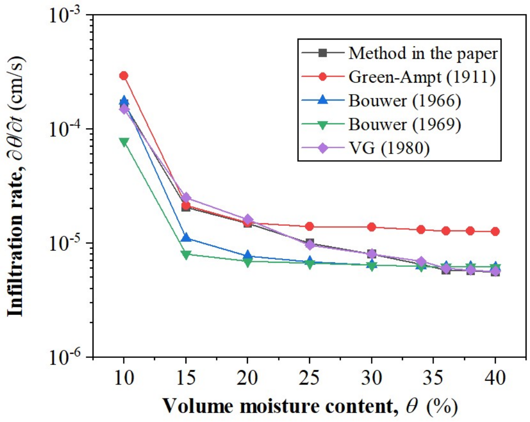

(**c**)

Figure 9. Comparison chart of numerical calculation results: (**a**) unconsolidated sand; (**b**) Touchet silty loam; (**c**) microsilica.

There is another advantage of the derivation formula based on the SWCC, which is that the air entry value does not need to be precisely determined.

The formula of the Green-Ampt model is greatly affected by the air entry value, which is difficult to be measured accurately. Bouwer revised the Green-Ampt model and reduced the value of saturated permeability coefficient k_s and air entry value s_t by half respectively. Small changes in the air entry value will still affect the calculation results. The formula proposed in this paper does not use the air entry value, but the slope between the air entry value and the residual water content on the SWCC, so it is only necessary to measure the shape of the SWCC. Moreover, while the van Genuchten–Mualem model has three parameters, the method proposed in this paper contains only one parameter, which can be easily obtained by penetration experiments.

5. Conclusions

This study believes that any point in the soil is often not in a state of hydrostatic equilibrium with the SWCC, and the movement of pore water is driven by the matric potential and the gravitational potential. The unsaturated one-dimensional vertical direction is obtained, combined with the law of conservation of mass and Darcy's law. The advantage of the theoretical formula proposed in this paper is that the parameters to be fitted are few and easy to obtain, and it does not need to measure the air entry value compared with classical models, such as the Green-Ampt model, the Bouwer formula, and the van Genuchten–Mualem model, and there will be no calculation errors caused by inaccurate air entry values. It can be found that, with the increase of soil burial depth, the higher the soil moisture content, and the smaller the matric suction, the infiltration rate becomes smaller, with the example. The calculation results of the method proposed in this paper are closer to the actual situation. The theoretical formula proposed in this paper is based on the assumption that the exponential expression of matric suction between the two inflection points of the SWCC (air-entry value and residual water content) is linearly related to volumetric moisture content. Moreover, the theoretical formula proposed in this paper can only be used for one-dimensional seepage calculation, and the influence of pore water movement in the x-axis and y-axis on practical problems is not considered in the process of derivation, and it can be improved in the future to derive the formula of two-dimensional and three-dimensional seepage.

Author Contributions: Conceptualization, S.W., X.G. and L.S.; methodology, L.S.; validation, T.W., L.S., X.G. and S.W.; formal analysis, S.W.; data curation, S.W.; writing—original draft preparation, S.W. and L.S.; writing—review and editing, L.S. and T.W.; supervision, L.S.; project administration, L.S.; funding acquisition, L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant numbers 52079018, 52108330.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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