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To cite this article: Yuting Bai and Keming Tang 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **585** 012176

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Experimental study on infiltration of unsaturated soil and solution of permeability coefficient

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Abstract: During the unsaturated infiltration, water content, infiltration rate, infiltration amount and other physical quantities are all related to the water supply approaches and intensities. In order to study the change of water migration and the permeability coefficient in vertical infiltration of one-dimensional soil column with different infiltration conditions, this paper designs an experimental device for a one-dimensional soil column infiltration model. Three sets of infiltration tests with different intensities were carried out in two ways: artificial rainfall infiltration and ponding infiltration. The results show that the infiltration under the conditions of rainfall infiltration and ponding infiltration presents a similar trend. The infiltration of ponding in the initial stage of infiltration has greater fluctuations than the infiltration of rainfall, but after the latter stabilizes, the infiltration capacity of ponding infiltration and rainfall infiltration tends to be the same. Finally, on the basis of the theory of soil water energy state and the law of conservation of energy, a new method for solving the permeability coefficient of unsaturated soil under free infiltration is obtained.

1. Introduction

The infiltration is an important link in the natural water cycle. Soil infiltration is closely related to human production activities, for example, the stability of slopes, roadbeds, dams and so on are all directly affected by soil infiltration[1]. For unsaturated soil the most common forms of infiltration under natural conditions are rainfall infiltration and ponding infiltration. At present, to research the characteristics of these two infiltration methods, the main research method is to monitor the migration of soil moisture. And the monitoring of water migration mainly includes the detection of soil water content and negative pore pressure. The characteristics of soil water migration can be understood through the monitoring of soil water content, and the monitoring of soil suction can achieve the same purpose. Usually these two variables are commonly used to study the relationship between the energy state and content of soil water.

In this paper, the research on the characteristics of rainfall infiltration and ponding infiltration is carried out by a combination of laboratory tests and theoretical basis. In the process of rainfall infiltration, when the rainfall intensity is less than the infiltration capacity of the soil, the infiltration will show pressure-free infiltration with no runoff. At this time, the infiltration rate is mainly determined by the intensity of the external water supply; When the rain is stronger than the infiltration capacity of the soil, runoff will occur, and the soil infiltration changes from non-pressure infiltration to pressure infiltration. At this time, the speed of soil water movement is mainly determined by the nature of the soil itself; while in the process of ponding infiltration, the pressure of the upper layer of water exists throughout the infiltration process, and the water migration rate in the early stage is mainly



determined by the intensity of water supply[2-3]. The later period is mainly controlled by the soil structure. In order to explore the influence of soil water energy state on soil water infiltration, this paper carried out a study on the mechanism of pressure-free infiltration based on the theory of soil water energy state.

Regarding the law of soil infiltration, predecessors have done a lot of research and achieved fruitful results. The vertical infiltration formula of Green-Ampt[4] has a certain physical basis, it is not suitable for heterogeneous soil with uneven initial water content, and the parameters are not easy to measure; The vertical infiltration formula of Philip[5] has strict requirements on applicable conditions and soil conditions; The empirical formula of КОСТЯКОВ is simple, but it is mostly used in the calculation of infiltration of farmland irrigation at the initial stage of infiltration or short infiltration time. However, when the water level is large, this formula cannot accurately describe the soil infiltration process, and the calculated intensity of long-term infiltration tends to zero, which is different from the actual monitoring results; In addition, Holtan's empirical formula is difficult to accurately calculate the submergence of a point, but it can also be used to estimate the rainfall in the basin. It can be seen that these classic formulas have limitations in practical applications, so the current research on soil moisture infiltration is still a research hotspot in soil hydrology.

This article attempts to combine laboratory experiments, classical physics and differential mathematics to study and discuss the effects of changes in soil water energy state on permeability coefficients. Classical physics believes that soil water is controlled by inertial force, resistance, capillary force, gravity, pressure and other forces, and the work done by these forces in the infiltration process gradually convert into the gravitational potential, pressure potential, matrix potential, solute potential, and temperature potential of soil water. Therefore, based on the law of conservation of energy, this paper proposes a new calculation method for the permeability coefficient of unsaturated soils by studying the changes in soil water content and wetting depth during the infiltration process.

2. Infiltration laboratory test

2.1. Experimental device

The one-dimensional vertical infiltration test device used in this article mainly includes: plexiglass column, pinhole rain device, soil moisture collector, as shown in Figure 1.

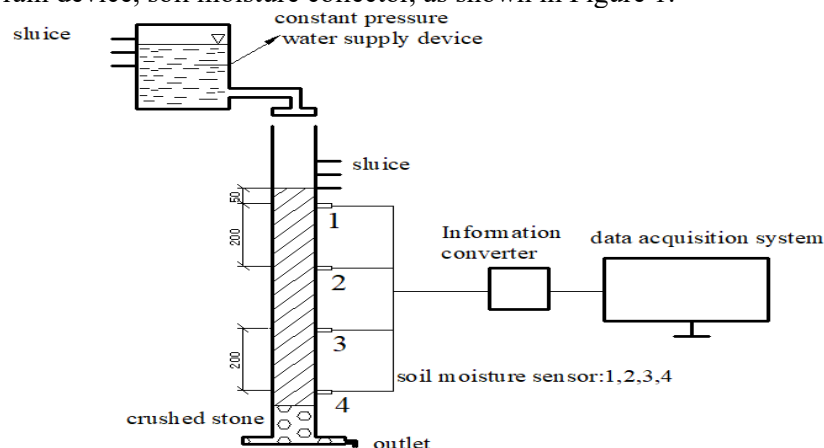


figure. 1 Diagram of infiltration test

The rainfall device is a pinhole artificial rainfall simulator composed of a 7-gauge needle[6]. The rainfall device controls the rain intensity by calibrating the water supply head to determine the water discharge valve of the water supply, so as to meet the experimental requirements of stable rainfall; the soil moisture collector used in the test consists of four soil moisture sensors, serial communication modular, and power adapters, data acquisition instrument. The soil moisture sensor is based on the principle of time domain reflection and can directly and stably reflect the true water content of various

soils by measuring the soil dielectric constant; the test plexiglass column has an outer diameter of 120mm, an inner diameter of 100mm, and a height of 1000mm. The upper part is equipped with 3 circles of drain valves to control the water pressure head, respectively 10mm, 30mm, and 50mm from the soil surface. The lower part is provided with a permeable layer of 80mm. A clear scale is affixed to the left to monitor the wet front dip. The sensor jack is reserved on the right, and the position is shown in Figure 1.

2.2. Test plan

The test soil is loam with a saturated volumetric water content of 43.1% and a dry density of 1.337. The loam was ground and air-dried, and then sieved through a 1mm standard aperture sample sieve to make a soil sample with an initial moisture content of 3%. Then control its dry density and compact it in layers every 50mm to make a 7000mm soil column.

Four sensors are placed on the soil column. The first sensor is 50mm away from the surface soil to monitor changes in the water content of the surface soil. The second, third, and fourth sensors are placed downwards at intervals of 200mm respectively to monitor the characteristics of stable infiltration of soil water in the soil.

A total of three soil column samples were set up during rainfall infiltration, and the tests were carried out at rainfall intensity of 20 mm/h, 30 mm/h and 40 mm/h. Record the wet front every 10 minutes. For one-dimensional infiltration of ponding, three soil column samples are also set up, and infiltration tests are carried out at depths of 10mm, 30mm, and 50mm respectively, and the depth of wet front infiltration is recorded according to the method of rainfall infiltration.

3. Analysis of results

3.1. Wetting peak process curve under rainfall and ponding conditions

When water infiltrates in the soil column, the wetting front appears at the sub-layer formed by the wet layer and the dry soil layer. The left graph in Figure 2 shows the time history curve of the wetting front with time under different rainfall intensities. In the graph, the rain intensity from bottom to top is 20mm/h, 30mm/h and 40mm/h. The right figure in Figure 2 represents the change of wetting peak of soil column under different water accumulation depth. The depth of accumulated water in the curve from bottom to top is 10 mm, 30 mm and 50 mm respectively. It can be seen from Figure 2 that the initial wetting front of the two types of infiltration is obviously faster than the later downward movement rate. This is due to the matric suction of soil column is very large at the initial stage, and the water can move down rapidly, but in the later stage the upper soil is in a stable state, its infiltration capacity will also decrease and become stable, and ultimately controlled by the soil's own infiltration capacity. The infiltration rate of wetting front is positively correlated with the water supply intensity, and the greater the water supply intensity, the faster the infiltration rate is. Although the change trend of the two wetting fronts is similar, the wetting front of ponding infiltration is obviously faster than that of rainfall infiltration in the early stage.

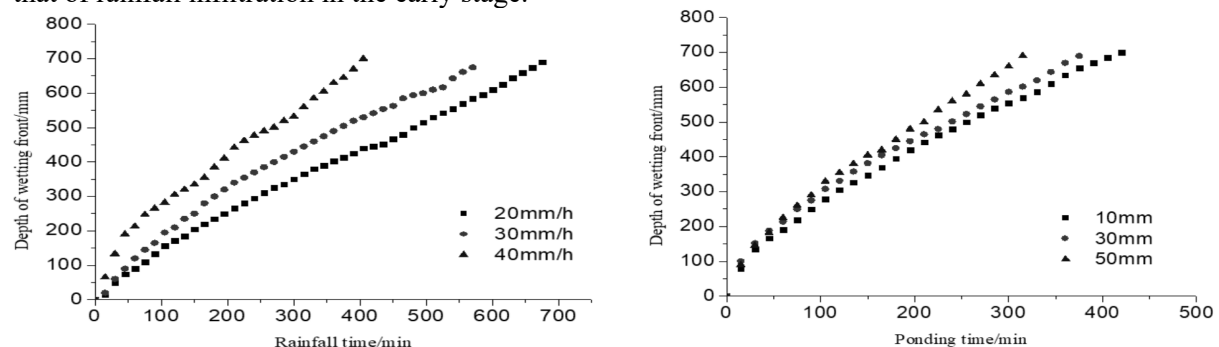


figure. 2 Time curves of wetting front depth in soil column under different rainfalls and different ponding conditions

3.2. Analysis of wetting front infiltration rate results

The left figure in Figure 3 shows the curve of wetting front infiltration rate with time under the rainfall intensity of 20mm/h, 30mm/h and 40mm/h. The right figure in Figure 3 shows the variation curve of soil column under water accumulation of 10 mm, 30 mm and 50 mm. In the rainfall infiltration test, the greater the rain intensity, the greater the initial wetting front infiltration rate. After reaching a stable infiltration in the later stage, the wetting front infiltration rates of the three are all stably distributed between $1 \text{ mm} \cdot \text{min}^{-1}$ and $0.5 \text{ mm} \cdot \text{min}^{-1}$. This is because the determinants of the later wetting front infiltration rate are mainly determined by the nature of the soil itself. The wetting front distribution of ponding infiltration rate and rainfall infiltration rate are basically similar, and they are divided into two periods. The deeper the water in the early stage, the faster the infiltration rate. After the later stage is stable, the infiltration rate is also distributed between $1 \text{ mm} \cdot \text{min}^{-1}$ and $0.5 \text{ mm} \cdot \text{min}^{-1}$. It is worth noting that the soil wet front infiltration rate under rainfall conditions all decreased to a stable state after the 200th minute, and the wet front infiltration rate under water accumulation conditions all decreased to a stable state after the 100th minute. In contrast, the wetting front infiltration rate of ponding infiltration is more stable, because the water supply capacity of ponding infiltration is stronger than that of rainfall infiltration, and the water absorption capacity of upper soil is better reflected. Therefore, in the actual production and life, the key to improve the soil infiltration rate is to improve the soil structure.

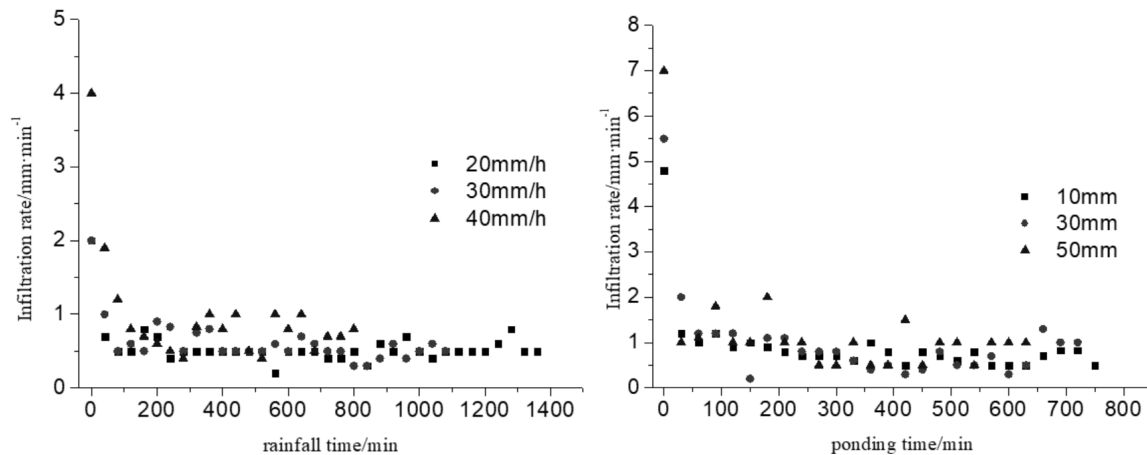


figure. 3 Time curves of wetting front infiltration rate in soil column under rainfalls and ponding conditions

3.3. Water content analysis of monitoring points

Figure 4 shows the time history curve of soil column volume water content under different rainfall intensity, and figure 5 shows the time history curve of soil column volume water content under different water accumulation depth. First of all, whether it is rainfall infiltration or ponding infiltration, the water content of the soil column is difficult to reach the fully saturated water content, and the maximum water content is distributed around 40%, but it is not much different from the saturated water content. This difference is mainly due to the complex stress of soil water infiltration in unsaturated soil, which leads to unstable movement in the pores of the soil, and it is difficult to fill all the tiny gaps. Secondly, during the compaction process of the soil sample, under the gravity of the upper soil, the lower soil will also cause a certain amount of closed voids, which makes it difficult for the soil column to be fully saturated. Secondly, comparing the changes in the surface soil water content of the soil column in Figure 4 and Figure 5, Under the condition of ponding infiltration, the water content of upper soil increases rapidly, and there was no obvious transition period in the infiltration process, and soon entered the stage controlled by the soil infiltration capacity. The water content of rainfall infiltration will go through a period of slow growth. The moisture content will first reach a larger value relatively quickly, then go through a period of slow rise, and finally reach the maximum moisture content and enter the control stage of soil infiltration capacity.

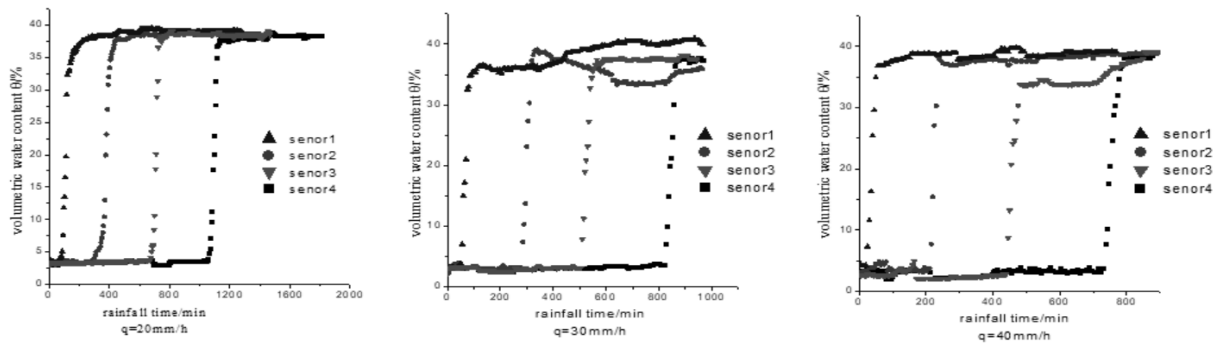


figure. 4 Time curves of volumetric water content at monitoring points under different rainfalls condition

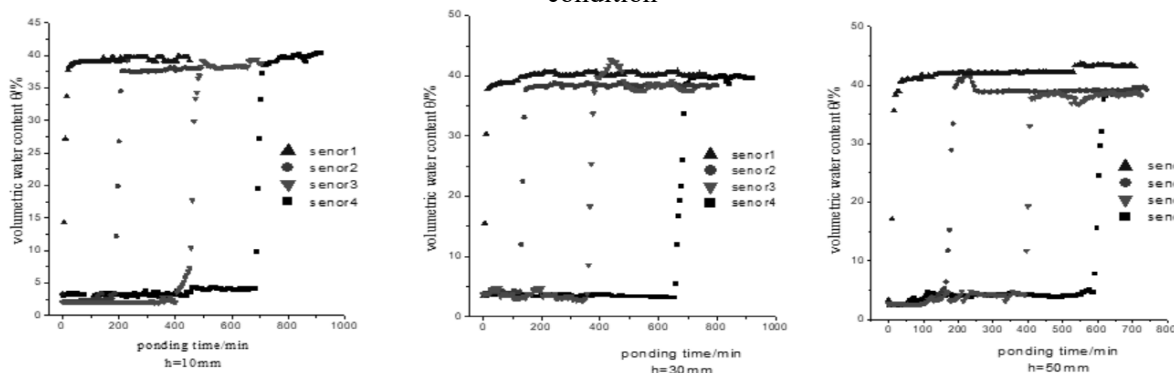


figure. 5 Time curves of volumetric water content at monitoring under different accumulated conditions

4. Calculation of permeability coefficient in pressure-free infiltration stage

4.1. Derivation of permeability coefficient

The unsaturated soil water mainly moves unsteadily in the soil voids under the action of capillary force, gravity and resistance [7]. Therefore, according to green Ampt model and Darcy's law, it is assumed that ① there is a clear horizontal wetting front in the soil column infiltration; ② the soil is a continuous skeleton and immutable porous medium. Because the soil water above the wetting front can ignore the solute potential, temperature potential and pressure potential[8], the soil water above the wetting front satisfies the following relationship:

$$\varphi_m + \varphi_g = \varphi'_m + \varphi'_g + E_g + E_p + E_c \quad (1)$$

In the formula: φ_m and φ_g are the matrix potential and gravitational potential of soil water at time t ; φ'_m and φ'_g correspond to the matrix potential and gravitational potential at time $t+\Delta t$, and E_g , E_p , E_c are the work respectively done by the gravity, capillary force and resistance of soil water from t to $t+\Delta t$ [8].

Since the study duration Δt is a small period, the quality change is ignored. Use linearization for equation (1), and use total head to represent the total potential energy of soil water, as shown in the following equation:

$$\begin{aligned} \varphi_m + \varphi_g &= \varphi'_m + \varphi'_g + m\Delta h \left[g + \left(h_p - \frac{1}{2}\Delta h_p \right) gP \left(y + \frac{1}{2}\Delta y \right)^{-1} - 4a \left(v - \frac{1}{2}\Delta v \right) (\rho d)^{-1} \right] \\ H_t &= H_{t+\Delta t} + \Delta h \left[1 + \left(h_p - \frac{1}{2}\Delta h_p \right) P \left(y + \frac{1}{2}\Delta y \right)^{-1} - 4a \left(v - \frac{1}{2}\Delta v \right) (g\rho d)^{-1} \right] \end{aligned} \quad (2)$$

In the formula: m is the mass of soil water above the wetting front at time t , Δm is the soil water mass loss from t to $t+\Delta t$, ρ is the soil water density, Δh is the infiltration height of soil water within Δt , h_p is the capillary head, Δh_p is the capillary head loss within Δt , y is the depth of the wetting front, v is the wetting front infiltration rate, Δv is the variable of the infiltration rate, a is the resistance coefficient, P is the capillary porosity, and d is the soil void diameter. H_t and $H_{t+\Delta t}$ correspond to the total head of soil water at time t and $t+\Delta t$, respectively.

According to the unsaturated Darcy's law, the permeability coefficient can be obtained:

$$K = v \left[1 + \left(h_p - \frac{1}{2} \Delta h_p \right) P \left(y + \frac{1}{2} \Delta y \right)^{-1} - 4a \left(v - \frac{1}{2} \Delta v \right) (g\rho d)^{-1} \right]^{-1} \quad (3)$$

Equation (3) reflects the relationship between infiltration rate of wetting front and infiltration rate, capillary head in the non-pressure infiltration stage. The larger the negative pressure head, the smaller the permeability coefficient, the greater the matrix potential, the smaller the permeability coefficient.

The classic unsaturated soil permeability coefficient model proposed by Mualem[9] is a function of effective saturation. Mualem[10] believes that in unsaturated seepage, the hydraulic conductivity when the pores are fully saturated is equal to the hydraulic conductivity in saturated seepage. However, the mechanism of saturated infiltration and unsaturated infiltration are not exactly the same. The model in this article is a function of negative pressure and infiltration rate, which can avoid the incomplete permeability coefficient of Mualem model.

4.2. Calculation example of unsaturated permeability coefficient

During rainfall infiltration, the non-pressure infiltration stage occurs before the accumulation of water. Therefore, the calculation example in this paper uses the data of No. 2 sensor of a soil column with a rainfall intensity of 20 mm/h before the accumulation of water to calculate the unsaturated permeability coefficient.

According to the soil-water characteristic curve of the soil sample, the formula (4) of negative pressure suction and water content is obtained by fitting the empirical formula[11] $s=A\theta^b$:

$$s = 7.638 \times 10^5 \theta^{-1.835} \quad (4)$$

In the formula: s is the soil water suction head, in mm, and θ is the soil volumetric water content.

Finally, the relationship between permeability coefficient and water content can be obtained:

$$K = v \left[1 + 7.64 \times 10^2 \left(\theta_t^{-1.835} + \theta_{t+\Delta t}^{-1.835} \right) P (2y + \Delta y)^{-1} - 4a \left(v - \frac{1}{2} \Delta v \right) (g\rho d)^{-1} \right]^{-1} \quad (5)$$

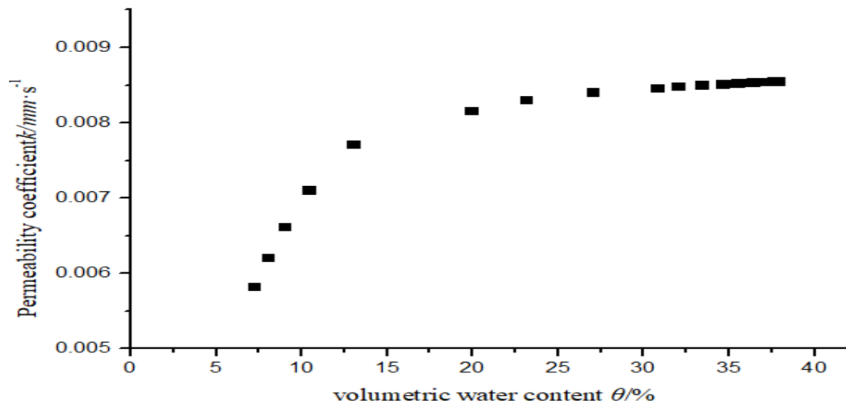


figure. 6 The curve of permeability coefficient

According to the height of the sensor, it can be known that y is 530mm, soil capillary porosity P is

13.645%, resistance coefficient a is $8.01 \times 10^{-4} \text{Pa} \cdot \text{s}$. Since the soil sample is a homogeneous soil, the pore diameter d is brought into the average value $50 \mu\text{m}$. Finally, the volumetric water content measured by the No. 2 sensor is brought into formula (5), that is, the permeability coefficient of the remolded soil under different water content is calculated, as shown in Figure 6.

It can be seen from Figure 6 that the permeability coefficient increases very rapidly at the stage with a small water content, and even shows a linear increase trend. But when the water content reaches 25%, the permeability coefficient tends to stabilize. This also explains the phenomenon that the permeability of dry soil is much greater than that of moist soil. Finally, it can be seen that the experimental results and theoretical calculations in this paper are consistent and reasonable.

5. conclusion and discussion

In this paper, the following main conclusions are obtained through the experimental study of infiltration and the derivation of permeability coefficient:

(1) The experimental results show that the soil column presents an obvious difference in the initial stage of rainfall infiltration and ponding infiltration, ponding infiltration has stronger infiltration capacity than rainfall infiltration; but after the later stage is stable, there is no obvious difference between water infiltration and rainfall infiltration.

(2) Solving the permeability coefficient of free infiltration on the basis of energy conservation can obtain the relationship between negative pressure or water content and permeability coefficient. In addition to free infiltration, the idea of pressurized infiltration can also be used for theoretical derivation, thereby combining free infiltration and pressurized infiltration into a continuous infiltration process.

Acknowledgments

This work is supported in part by National Natural Science Foundation of China (41601288).

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