# Influence of permeability on rainfall infiltration based on water gas two phase flow

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**Abstract.** The permeability function is one of the key properties in unsaturated soil mechanics and variation of parameters in soil water characteristic curve can easily affect matric suction as well as infiltration. The purpose of this research is to explore the significant effect of parameters in SWCC on rainfall infiltration. A water gas two phase flow analysis method was conducted to investigate the influence of parameters in SWCC on stable infiltration intensity. Result showed that when saturation was low, stable intensity of infiltration was greatly affected by matric suction because the modified parameters were related to pore size distribution such as air entry value $p_0$ and parameter m. When saturation was close to 1,the influence of soil infiltration intensity was almost not affected by matric suction. The minimum value of stable infiltration of intensity was mainly determined by the intrinsic permeability, while saturation of this value was mainly affected by soil water characteristic curve, intrinsic permeability coefficient of soil as well as water relative permeability coefficient.

## 1 Introduction

Continuous rainfall and heavy rainfall events have become an increasing component for geological disasters such as mudslide and landslide [1]. The infiltration of rainwater in unsaturated soil leads to the movement of water flow and gas flow, which can change the unsaturated characteristic of slope soil and cause slope failure [2]. Unsaturated seepage characteristic of soil includes the soil water relationship and water-air permeability relationship, which is a comprehensive reflection of soil microstructure on macro level. Therefore, numerical simulation of infiltration process under different unsaturated seepage characteristic is of great significance to reveal the infiltration law of soil under multiple physical characteristic variables.

Unsaturated seepage and its effect on infiltration have been studied by many researchers. Wu [3] demonstrated the pressure head distribution and the infiltration effect caused by unsaturated seepage were greatly affected by the boundary condition and some parameters. Kao [4] set an unsaturated soil column test then captured the fundamental physics of unsaturated fluid flow and analysed the infiltration process by modifying permeability parameters. Later the computational method was also developed by some scholars. Hamdhan [5] estimated the hydraulic parameters required for the Van Genuchten model then the agreement achieved in pore-water pressures and ground water level can be considered. However, these studies including test and numerical simulation were mainly based on the one single phase such as water flow phase. Some other researchers focused the study of two phase flow including air flow and water flow. Lam [6] calculated stress state for unsaturated soil by two dimensional finite element method under the assumption that gas in the unsaturated zone was regarded as continuum then vented to atmosphere. Dongmei Sun [7] simulated the rainfall infiltration process of soil slope and analysed the

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influence of air flow on water infiltration. Rainfall infiltration was a unsaturated seepage process that included the coupling process of water and gas two phase. Previous studies were mainly focused on the influence of external factors on the law of rainfall infiltration, while it was of great significance to analyse the influence of unsaturated permeability characteristic on the rainfall infiltration such as soil water characteristic curve and the permeability relationship of water and gas.

As a result, this study adopted the finite element method to research infiltration process under the condition of various permeability characteristic according to the unsaturated soil water gas two phase flow and analysed the influence of soil water characteristic curve on stable intensity of infiltration. It is of great importance to know mechanism of slope failure that triggered by rainfall infiltration and improve the forecast and prediction of landslide. This can also provide reference to some engineering problems such as controlling flood problem, water-saving irrigation as well as transport of pollutants.

## 2 Water-gas Two Phase Computational Model

### 2.1 Differential Equations for the Control of Water and Gas

The liquid phase flow equation and gas phase flow equation are included in the water gas two phase basic governing equation. The coupling of water gas two phase flow is realized by correlation of porosity, matric suction, saturation as well as pore gas pressure and some other variables. The flow of liquid phase and gas phase need to be satisfied with mass conservation equation that driven by pressure. Meanwhile soil deformation, compressibility, viscosity as well as the variation of saturation of water and gas can also be considered.

As a result, the liquid flow equation could be written as follows based on the law of conservation of mass [8]:

$$\frac{\partial(\varphi S_r)}{\partial t}+\nabla\cdot[-\frac{k_{rw}k}{\mu_w}(\nabla p_w+\rho_w g)]-\frac{Q_w}{\rho_w}=0 \quad (1)$$

where φ is the porosity, $S_r$ is the degree of saturation, $\mu_w$ is the viscosity coefficient of the water phase ($P_a\cdot s$), $k_{rw}$ is the relative permeability coefficient of the water phase, k is the intrinsic permeability of soil ($m^2$), $p_w$ is the pressure of the water phase ($P_a$), $Q_w$ is the source of water phase ($kg/(m^3\cdot s)$), $\rho_w$ is the density of the water phase ($kg/m^3$), g is the gravitational acceleration.

According to the law of conservation of mass, the gas flow governing differential equation could be written as follows [8]:

$$\frac{\partial[(1-S_r)\varphi]}{\partial t}+\nabla\cdot[-\frac{k_{rg}k}{\mu_g}(\nabla p_g+\rho_g g)]-\frac{Q_g}{\rho_g}=0 \quad (2)$$

where φ is the porosity, $S_r$ is the degree of saturation, $\mu_g$ is the viscosity coefficient of the gas phase ($P_a\cdot s$), $k_{rg}$ is the relative permeability coefficient of the gas phase, k is the intrinsic permeability of soil ($m^2$), $p_g$ is the pressure of the gas phase ($P_a$), $Q_g$ is the source of gas phase ($kg/(m^3\cdot s)$), $\rho_g$ is the density of the gas phase ($kg/m^3$), g is the gravitational acceleration.

### 2.2 Constitutive model and parameters

There are five unknown parameters in the equation (1) and equation (2) such as $S_r$, $p_w$, $p_g$, $k_{rw}$, $k_{rg}$. In order to solve these two equations, three constitutive relationship need to be involved in this calculation including soil water characteristic curve, relative permeability coefficient of water and gas. In this research, the sandy soil was selected to do this calculation.

#### *2.2.1 Soil-water characteristic curve*

The relationship between water saturation and matric suction was described by soil-water characteristic curve. The van Genuchten numerical model was selected in this research. In this research, matric suction in soil is defined as the difference between pore gas pressure and pore water pressure. The van Genuchten model can be written as follows [9]:

$$p_c=-p_0[(\frac{S_r-S_{rw}}{1-S_{rw}})^{-\frac{1}{m}}-1]^{1-m} \quad (3)$$

where $p_c$ is the matric suction, $p_0$ is the air-entry pressure, $S_{rw}$ is the residual degree of water saturation, and m is a model parameter that related to the material.

### *2.2.2 Relative permeability coefficient of water*

The relative permeability coefficient of water reflects the connection between relative fluidity of water and water saturation. In this research, the van Genuthten-Mualem model was selected because of its broad applicability [10].

$$k_{rw} = (\frac{S_r - S_{rw}}{1 - S_{rw}})^{0.5} \cdot \{1 - [1 - (\frac{S_r - S_{rw}}{1 - S_{rw}})^{1/n}]^n\}^2 \quad (4)$$

where $k_{rw}$ is the relative permeability coefficient of water, n is a model parameter that is related to the material.

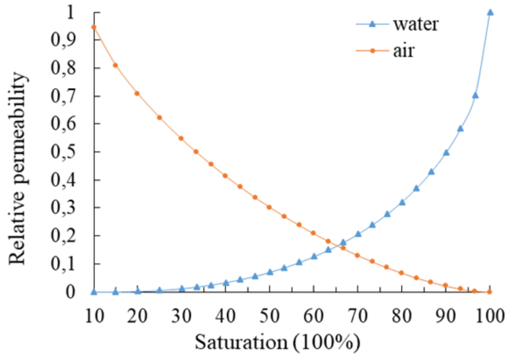
### *2.2.3 Relative permeability coefficient of gas*

The relationship between relative fluidity of gas and water saturation can be described by the relative permeability coefficient of gas. In this study, the Brooks-Corey model was selected because this model works satisfactorily in many cases and has been utilized widely for several decades [11]:

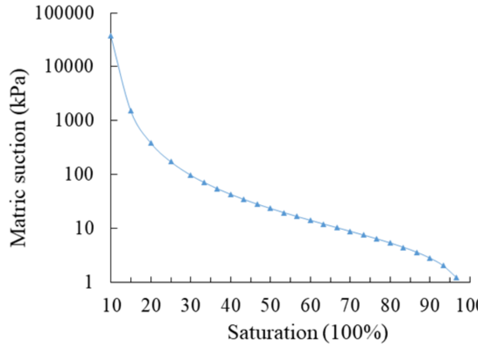
$$k_{rg} = (1 - \frac{S_r - S_{rw}}{1 - S_{rw} - S_{rg}})^{0.5} \cdot [1 - (\frac{S_r - S_{rw}}{1 - S_{rw} - S_{rg}})^{1} \quad (5)$$

where $k_{rg}$ is the relative permeability coefficient of gas, $S_{rw}$ is the residual degree of water saturation, $S_{rg}$ is the residual degree of air saturation.

Fig.1 shows the relative permeabilities of water and air curve and the soil water characteristic curve. Some other basic values of parameters included in this research was also shown in table 1.




a) Relative permeabilities of water and air




b) Soil water characteristic curve

**Fig.1.** Hydraulic characteristics for seepage analysis.

**Table 1.** Parameters for the numerical simulation.

| **Name of parameters** | **Sandy soil** |
|---|---|
| Initial intrinsic permeability ($m^2$) | $5.8 \cdot 10^{-12}$ |
| Gravitational acceleration g ($m/s^2$) | 9.8 |
| Residual water saturation ($S_{rw}$) | 0.1 |
| Residual gas saturation ($S_{rg}$) | 0.05 |
| Water viscosity ($kg/m \cdot s$) | $1.0 \cdot 10^{-13}$ |
| Air viscosity ($kg/m \cdot s$) | $1.8 \cdot 10^{-5}$ |
| Initial porosity | 0.35 |
| Capillary pressure: equation (3) with $p_0$ | 1.5 |
| Capillary pressure: equation (3) with m | 0.445 |
| Initial water density ($kg/m^3$) | 1000 |
| Initial air density ($kg/m^3$) | 1.25 |

### 2.3 Geometric model

As for soil slope, direction of natural infiltration was vertical, infiltration of water was mainly focused on shallow area of the slope. In this research, the geometric model of this research was shallow homogeneous soil. The one-dimensional homogeneous sandy soil column model

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was calculated. The height of this model was 3 m, the width of this model was 1.2 m. The number of computing element was 992 with 1071 nodes. In addition, the grid was dense on top and sparse on bottom. Thickness of the minimum cell was 0.1m.

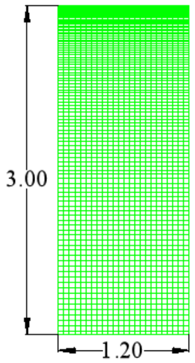


**Fig.2.** Finite element meshes of soil column.

## 3 Influence of Soil-water characteristic curve relationship on intensity of infiltration

Relationship between soil matric suction and saturation is described by soil water characteristic curve. In this study, van Genuchten model was adopted to describe this relationship. The variation of the parameter m and $p_0$ can directly affect the appearance of the SWCC. In this study, the variation of parameter m and $p_0$ was researched separately. The relative intensity of infiltration was adopted as to compare the influence of seepage characteristic on infiltration intensity. It was also defined as the ratio of rainfall infiltration rate to saturated permeability coefficient of soil.

### 3.1 The influence of parameter m on infiltration intensity

Parameter m is an important parameter that reflects soil pore structure characteristics, it is also related to pore size distribution. In order to research the influence of pore size distribution on intensity of infiltration, the process of infiltration was simulated under various values of m. Common value range of m is from 0.3 to 0.5. In this study, the value of m was 0.3, 0.35, 0.4, 0.45, 0.5. The value of saturation was from 0.15 to 1. Other parameters were shown as follows: $p_0$ =0.278, k=0.9. As shown in figure 3, the change rate of matric suction with saturation was affected by the parameter m. When saturation was less than 0.2, matric suction was greatly affected by the parameter; when saturation was close to 1, variation of parameter m had less effect on matric suction. Therefore, variation of parameter m can only affect matric suction at lower saturation. With the increase of saturation, the effect of matric suction on variation of m is not obvious.

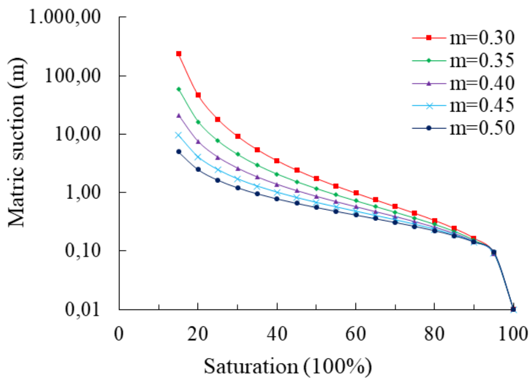


**Fig.3.** Soil water characteristic curve under various m.

In addition, stable intensity of infiltration was only affected by the parameter m for soil at lower saturation. In the figure 4, when saturation was close to 1, infiltrated channel in soil was mainly infiltrated by water, and it was not affected by matric suction. As a result, stable intensity of infiltration was not affected by the parameter. The saturation and value of the minimum intensity of infiltration was not varied by the variation of parameter m.

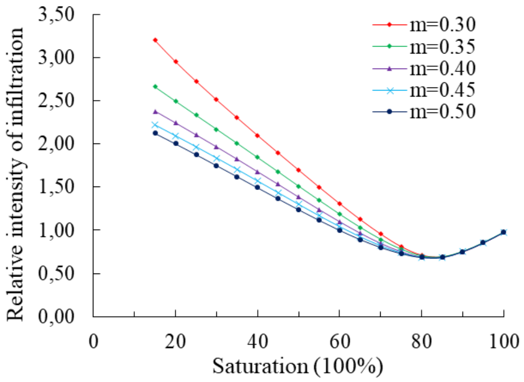


**Fig.4.** The relationship between relative intensity of infiltration and saturation under various values of m.

### 3.2 The influence of parameter $p_0$ on intensity of infiltration

By simulating infiltration process under different values of $p_0$ , the influence of maximum pore size on infiltration intensity was studied. The range of this parameter is from 0.2 to 2. In this calculation, there was 5 values of $p_0$ including 0.2, 0.6, 1.0, 1.4, 1.8. There was also 18 values of initial saturation from 0.15 to 1, m=0.359 and k=0.9. As a result, 90 groups of calculation were simulated in this research. The change rate of matric suction with saturation was affected by parameter $p_0$. As is shown in figure 5, when saturation was less than 0.2, matric suction was greatly affected by this parameter; when saturation was close to 1, matric suction was mainly affected by water relative permeability coefficient, variation of parameter $p_0$ had small effect on matric suction until 0.

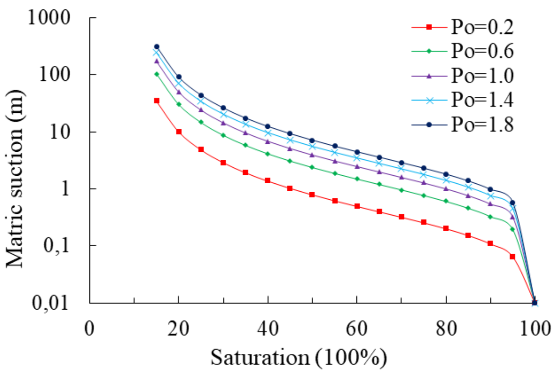


**Fig.5.** Soil water characteristic curve under various $P_0$.

It was clear to analyze in the figure 6 that with the increase of saturation, intensity of infiltration decreased firstly then increased. Intensity of infiltration increased with the increase of parameter $p_0$ under the same saturation condition. When saturation was large, matric suction increased with increase of parameter $p_0$, intensity of infiltration was obviously affected by matric suction so that minimum value of the intensity of infiltration moved to higher saturation point. When saturation was close to 1, water was mainly moved by soil pore channel, water relative permeability coefficient was the main reason that affected the infiltration, as a result, infiltration intensity was not affected by matric suction.

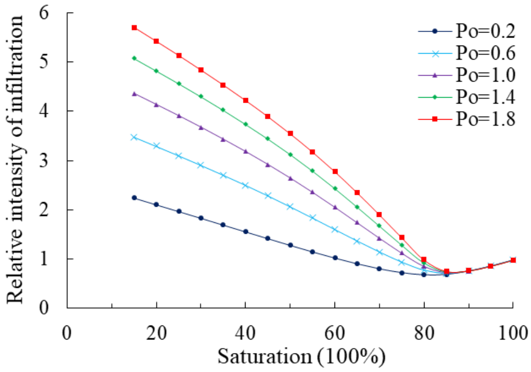


**Fig.6.** The relationship between relative intensity of infiltration and saturation under various values of $P_0$.

## Conclusions

Exploring the influence of unsaturated permeability of soil under the condition of rainfall infiltration is a meaningful topic. The finite element method was used to simulate rainfall infiltration process under various unsaturated infiltration characteristics according to the water gas two phase flow. The correlation between different seepage characteristics and stable infiltration intensity was also analysed.

(1) During the process of unsaturated infiltration, variation of matric suction can affect water pressure gradient in water infiltration process. Intensity of infiltration was obviously affected by matric suction under the condition of small saturation and small parameter m. When saturation was close to 1, intensity of infiltration was not affected by the parameter m.

(2) When saturation was small, water infiltration was driven by matric suction, as a result, intensity of infiltration varied obviously with the increase of parameter $p_0$. When saturation was large, water relative permeability coefficient was relative large, at this period, the main infiltrated channel for water was the pore channel, the intensity of infiltration was weakly affected by the increase of the parameter $p_0$.

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