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Simulation Monitoring for Rainfall Infiltration in Soil Based on High Density Electrical Method

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Abstract

Rainfall infiltration is a porous medium flow problem with variable saturation. Based on the theoretical analysis of the flow field, electrical conductivity of rocks, the electrical field, the paper simulates the coupling relationship between the water saturation in soil and the apparent resistivity distribution. It combines the Richards equation, the Archie formula and the Laplace equation. The experiment simulates the potential field data by the Wenner setting in electrical exploration on a two-layer geologic model with continuous rainfall during 5 days, which shows that the effective saturation in soil is increasing with the rainfall time, while the apparent resistivity is decreasing. This can provide a theoretical basis for the analyzing the rainfall infiltration and porosity of the soil by using high-density electrical method in the future.

Keywords

Rainfall Infiltration, Multi Physical Field Coupling, Numerical Simulation, High Density Electrical Method

1. Introduction

The analysis of rainfall infiltration is one of the most important problems in soil mechanics. In the process of rainfall infiltration, rainfall intensity and soil porosity will affect the soil seepage. How to evaluate and monitor rainfall infiltration by using geophysical methods is a multi physical field coupling problem, which also has important practical significance. Based on simulating with the Tianchi of the Changbai Mountain located in Northeast China, LI analyzed the multi physical field coupling response with the flow field, electric field and magnetic field, and provided some advices for the exploration, monitoring and development of volcanic areas (Hong-qing Li et al., 2017). LI analyzed the coupling response about the seepage with deformation in the unsaturated soil, and found

that the coupling effect is significant (Bin'e Li et al., 2014). Used high-density electrical method to continuously monitor the ore body during rainy season, ZHANG analyzed the data accumulation of apparent resistivity and the real-time change of contour map, which shown the formation and change process of the sliding surface, proposed the possibility of landslide geological disaster (Kai-wei Zhang et al., 2017). MA proposed the recognition characteristics of the sliding surface from the landslide monitoring experiment used the high-density electrical method in the Baishuihe of the Three Gorges Reservoir area, China (Guo-kai Ma et al., 2016).

In order to further explore the changes of flow field, stratum conductivity and geoelectric field caused by rainfall infiltration, this paper simulated the multi physical fields under different rainfall time, and acquired the high-density electrical data and inversion of geo-electrical structure about the modelling area.

2. Basic Theory of Multi Physical Field Coupling

The infiltration process of rainfall in soil is a complex problem. Rainfall infiltration will cause the change of stratum seepage, which leads to the increase of surface water content and the effective saturation of soil, and then affects the resistivity of soil and changes the physical characteristics of soil. This characteristic provides a theoretical basis for the use of high-density electrical method to monitor the formation structure.

2.1. Analysis of Seepage Field

According to the theory of groundwater dynamics, Richards equation can describe the rainfall infiltration process of unsaturated soil. The governing equation of the model is as follows:

$$\left[C + SeS\right]\left(\partial Hp/\partial t\right) + \nabla\left[-K\nabla\left(Hp + D\right)\right] = 0 \tag{1}$$

where, Hp is the pressure head; C is the specific water capacity; Se is the effective saturation; S is the storage coefficient; t the time; K is the permeability coefficient; and D is the coordinates of vertical elevation (such as x, y, z).

Further, the empirical formula proposed by Van Genuchten (M. Th. van Genuchten, 1980) can elaborate the quantitative relationship between Hp and θ.

$$\left(\theta - \theta_r\right)\big/\left(\theta_s - \theta_r\right) = \left(1\big/\left(1 + \left(\alpha Hp\right)^n\right)\right)^m \left(m = 1 - 1/n, 0 < m < 1\right) \tag{2}$$

where, θ_s is the saturated soil moisture content, θ_r is the residual moisture content, m, n and α is the empirical coefficient determined by the test, $m = 1 - 1/n$, $0 < m < 1$ (Jin-zhong Yang et al., 2009).

2.2. Basic Theory of Rock Physics

Rainfall infiltration changes the characteristic value of the soil effective saturation, and then affects the resistivity of the soil. The resistivity of the soil will be changed with the amount of water in soil. In generally, the higher the water

content of rock is, the lower the rock resistivity is. Archie formula is usually used to describe the relationship between the rock resistivity and the water saturation about the soil.

$$\rho = a\Phi^{-m}S_e^{-n}\rho_0 \tag{3}$$

where, ρ is the rock resistivity, ρ_0 is the resistivity of water filled in the pores, Φ is the porosity, n is the saturation index, m is the porosity index, usually varying from 1.5 to 3.0, a is the scale factor, ranging from 0.6 to 1.5. When other conditions remain unchanged, the rock resistivity decreases with the increase of water saturation (Jin-ming Li, 2005). It shows that the continuous rainfall makes the physical properties of soil different from that before infiltration, which becomes the basis of high-density electrical exploration.

2.3. Electric Field Analysis

In the electrical exploration, the electric field about the surface can represent the different stratum structure due to different rock resistivity. By measuring the distribution of the surface electric field, we can understand the underground situation. Using cylindrical coordinate system, the electric potential distribution satisfies the Laplace equation.

$$\partial^2 U / \partial r^2 + (1/r)(\partial U / \partial r) + \partial^2 U / \partial z^2 = 0 \tag{4}$$

Use the method of separating variables to find the solution of Equation (4), let:

$$U(r, z) = R(r)Z(z) \tag{5}$$

where, $R(r)$ is the undetermined function with only independent variables, $Z(z)$ is the undetermined function with only independent variables, Substituting Equation (5) into Equation (4):

$$-\left(d^2 R(r)/dr^2 + (1/r)dR(r)/dr\right)/R(r) = \left(d^2 Z(z)/dz^2\right)/Z(z) \tag{6}$$

After calculation, the general solution of Equation (4) is:

$$U(r, z) = \int_0^\infty \left[A(m)e^{-mz} + B(m)e^{mz} \right] J_0(mr) dm \tag{7}$$

where, $A(m)$ and $B(m)$ are functions of the undetermined integral variables m. $J_0(mr)$ is the zero order Bessel function for the solution.

According to the first boundary condition of stable current field, the potential formula of the first layer can be obtained as follows:

$$U_1 = \int_0^\infty \left[(\rho_1 I/2\pi)e^{-mz} + B_1(m)\left(e^{mz} + e^{-mz}\right) \right] J_0(mr) dm \tag{8}$$

The potential from the second layer to the $(n-1)$ layer is as follows:

$$U_i = \int_0^\infty \left[A_i(m)e^{-mz} + B_i(m)e^{mz} \right] J_0(mr) dm \quad (i = 2, \cdots, n-1) \tag{9}$$

Due to the electrical sounding work is carried out on the ground, only the potential distribution on the ground surface ($z = 0$) is studied, therefore only the potential distribution $B_1(m)$ is needed. Finally, the expression of potential on the

ground ($z = 0$) is obtained:

$$U_1(r,0) = \int_0^\infty \left[(\rho_1 I/2\pi) + 2B_1(m) \right] J_0(mr)\, dm \qquad (10)$$

The surface potential will be variable with the underground rock resistivity structure. In practice, it is the parameters about the potential difference and the DC current that the high density resistivity method can acquire, which can comprehensively reflect the inhomogeneity of underground electrical properties and the undulation of terrain by the apparent resistivity.

$$\rho_s = K(\Delta U/I) \qquad (11)$$

where, ρ_s is the apparent resistivity; K is the device coefficient, in meters, determined by the relative position of the source electrodes and receiver electrodes; I is the current supplied; ΔU is the potential difference between the measuring electrodes.

3. Numerical Simulation

In order to study the influence of rainfall infiltration on the seepage field and physical field of soil, a two-layer model with different porosity is established. The horizontal length for simulation is 50 m and the depth of the first layer is 10 m, the other parameters are shown in **Table 1** and their physical meaning is consistent with the formulas above. The rainfall intensity is 20 mm/h.

The process of rainfall infiltration model is simulated by Richards model interface in COMSOL Multiphysics software. Under the rainfall intensity of 20 mm/h, the change of effective saturation is simulated when the rainfall is keeping in 1 day, 2 days, 3 days and 5 days, as shown in **Figure 1**. It can be seen that with the increase of rainfall time, the effective saturation of the surface is gradually increasing, reaching saturation first, and then infiltrating downward, which gradually expands the range of effective saturation increase below.

Figure 1 describes the flow field about rainfall infiltration. The Archie's formula can represent the variation about the rock resistivity with water saturation, which can be the hinge from the flow field to the electric field. According to Archie formula, the change cloud of rock resistivity changes in 1 day, 2 days, 3 days and 5 days is simulated, as shown in **Figure 2**. With the increase of rainfall time, the resistivity of upper surface rock is decreasing and the range is gradually expanding. The simulation results confirm that rock resistivity is affected by effective saturation.

In order to acquire the potential distribution and variation with time, there are 24 electrodes are arranged on the surface of the model. Every two electrodes are separated by 2 m. The Wenner device in electrical exploration is used. And the given voltage is +12 V and −12 V respectively, and the current is 1 A. Then

Table 1. Parameter values.

Model	θ_s	Ks [m/h]	α [1/m]	n	a	m
Upper	0.5	0.25	1	2	1	1.3
Lower	0.1	0.25	1	2	0.8	2.3

the apparent resistivity values of different positions are obtained. As shown in **Figure 3**, it can be seen that the variation of apparent resistivity at different electrode distances, which can be depicted the rock resistivity about different depths. With the increase of rainfall time, the apparent resistivity values at the same depth are constantly decreasing. At the same time, the larger the formation depth is, the higher the apparent resistivity is. It is the coupling of seepage field and electric field. With the increase of effective saturation, the resistivity of rock decreases and the apparent resistivity decreases.

Through inversion, the resistivity structure about the geo-model can be described as shown in the **Figure 4**. It can be seen that the red area represented
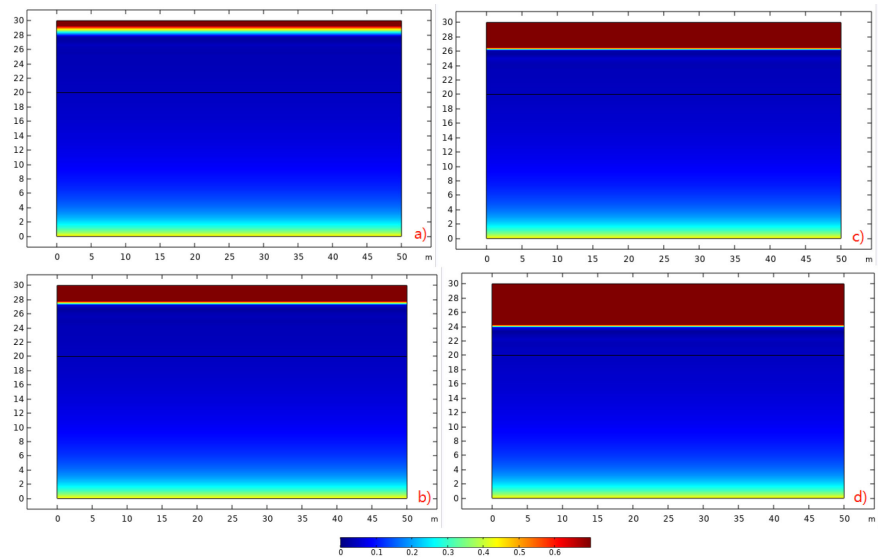

Figure 1. The change of effective saturation in different rainfall time: (a) 1 day, (b) 2 days, (c) 3 days and (d) 5 days.
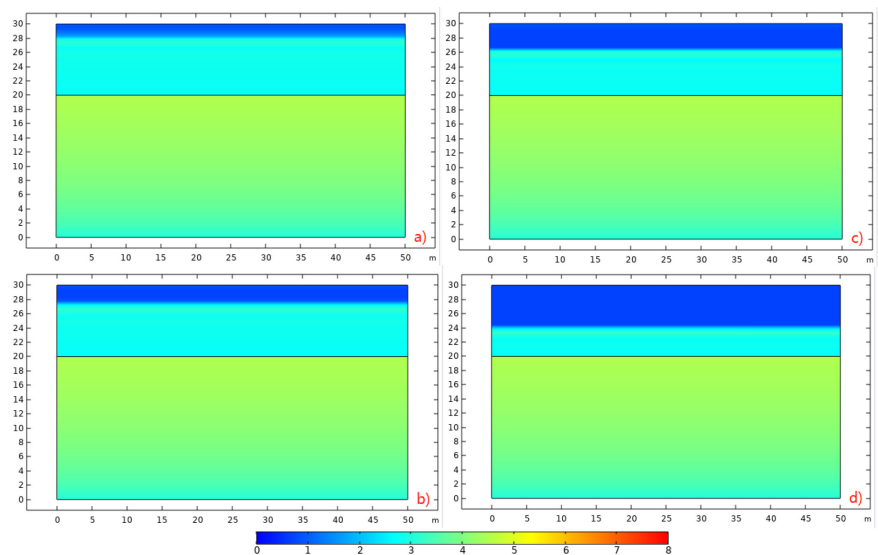

Figure 2. The change of rock resistivity change in different rainfall time: (a) 1 day, (b) 2 days, (c) 3 days and (d) 5 days.
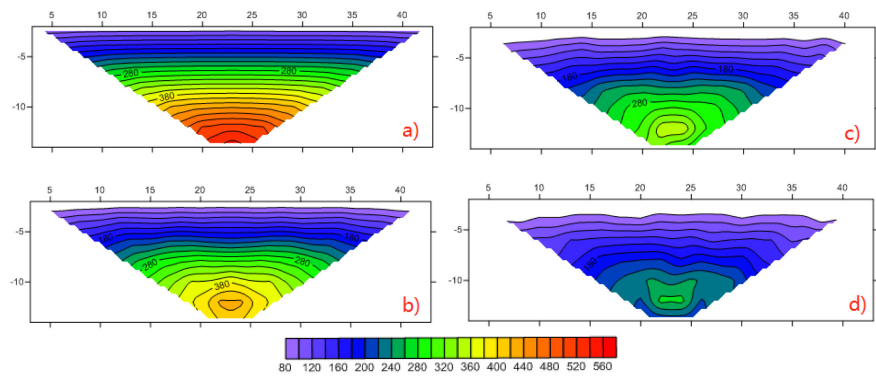
Figure 3. Apparent resistivity contour map in different rainfall time: (a) 1 day, (b) 2 days, (c) 3 days and (d) 5 days.
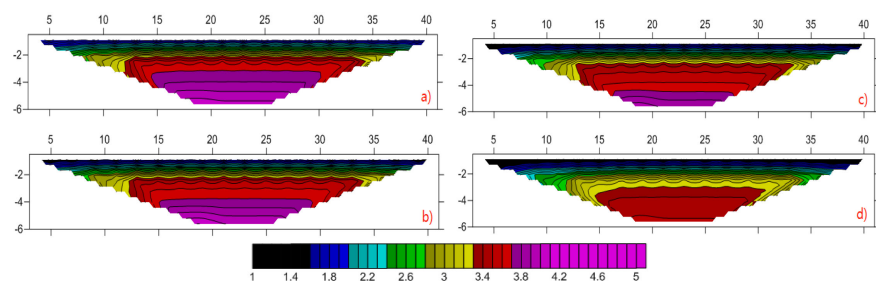

Figure 4. Inversion model resistivity contour map in different rainfall time: (a) 1 day, (b) 2 days, (c) 3 days and (d) 5 days.

higher resistivity values is expanding downward and the formation resistivity is decreasing. Through the change of the physical characteristics of the electric field, we can study the influence of different rainfall and porosity on the formation physical field. Combined with electrical exploration to monitor the change of resistivity, in turn, the rainfall infiltration with different porosity can be measured and evaluated.

4. Conclusion

Based on the multi physical field coupling theory, the paper presents the numerical simulation for the response about rainfall infiltration and electric field in soil, which verifies that the soil seepage field has a certain influence on the physical field in the process of infiltration. The research shows that under a certain rainfall intensity, the effective saturation increases with the increase of rainfall time, while the resistivity decreases. Through acquiring the potential field data by the Wenner setting in electrical exploration and calculating the apparent resistivity values, and then inverting the electric resistivity structure, the testing result shows that with the increase of rainfall time, the effective saturation is increasing, while the apparent resistivity is decreasing. The higher the water content is, the lower the resistivity is. This can provide a theoretical basis for the inversion of rainfall infiltration soil seepage field by using high-density electrical method to monitor the formation apparent resistivity in real time in the future.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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