On The Flow Of Water Through Large Pores In Porous Media

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Introduction

Large pores play an important role in porous media flow. They behave like bypassing flow channels contributing fast flow through porous media. Almost all of the existing models for flow of water through partially saturated large pores are conceptual and lack experimental observation. In this study we proposed a kinematic wave model based on physical process to simulate partially saturated flow through large pores. We developed a new equation for partially saturated laminar pore flow which we applied in the simulations. The applicability of this model has been verified with laboratory experiments on sand columns.

Estimating Large Pore Size Distribution

Before we go for modeling partially saturated flow through large pores, we need large pore size distribution of the porous media. In this study we applied saturated water breakthrough curve method of Radulovich et al. (1989) to estimate the effective large pore size distribution of the studied porous media. The analysis procedure of water breakthrough curve method is to combine the basic flow equation (Eq.1) with Hagen-Poiseuille's laminar flow equation (Eq.2) to solve for pore radius R (Eq.3). We used 1.5 as the tortuosity T of the large pores.

$$Q_s = \pi R^2 \left(\frac{TL}{t}\right) \tag{1}$$

$$Q_s = \frac{\pi g}{8\nu} R^4 \left(\frac{\Delta H}{TL}\right) \tag{2}$$

$$R = T \sqrt{\frac{8\nu L}{gt\left(\frac{\Delta H}{L}\right)}} \tag{3}$$

Simulating Partially Saturated Flow Through Large Pores

From the basic force-balance principle, partially saturated laminar flow discharge Q_p for a vertical cylindrical tortuous pore of radius R can be derived as, Eq.4 (Beven and Germann, 1981); where $(R\text{-}f)$ is the width of sheet flow (Fig.1) and $\Delta H/L = 1$. Eq.4 is cumbersome to deal with. From Eq.4 we derived a new equation for partially saturated large pore flow, Eq.5; where $K_p = Q_p/(\pi R^2)$ is the unsaturated hydraulic conductivity, $K_s = Q_s/(\pi R^2)$ is the saturated hydraulic conductivity, $S_d = (\pi R^2)/[\pi(R^2-f^2)]$ is the degree of saturation and α and β are the kinematic wave parameters. Eq.5 is similar to regular power form expressions for unsaturated hydraulic conductivity-moisture content $(K\text{-}\theta)$ relationship of the matrix part of porous media and is very convenient to apply in simulation.

$$Q_p = \frac{\pi g}{8\nu}\left(R^4 + 3f^4 - 4f^2R^2 + 4f^4 ln\frac{R}{f}\right)\left(\frac{\Delta H}{TL}\right) \tag{4}$$

$$K_p = \alpha S_d^{\beta} = (0.955K_s)S_d^{3.23} \tag{5}$$

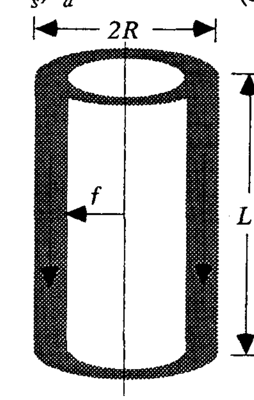

Fig.1 Partially Saturated Pore Flow

In this study we proposed kinematic wave equation for partially saturated flow through each large pore to be in terms of degree of saturation, Eq.6 from which kinematic wave celerity C_k and time of outflow since the onset of input t_{out} can be obtained as shown in Eq.7 and 8 respectively. Thus Eq.4 through Eq.8 gives the complete description of kinematic wave simulation for a single large pore. In brief the simulation procedure is to solve for degree of saturation of a large pore representative of a certain pore range (Eq.4), where input I would be the unsaturated hydraulic conductivity of that pore. Once the degree of saturation is known, kinematic wave celerity (Eq.7) and hence the time of outflow (Eq.8) for that pore can easily be solved. Step outflow for the pore range would be the outflow multiplied by the total number of pores of the representative pore size and the total outflow Q for a certain time period would be the sum of step outflows for different pore ranges. Finally Q-t_{out} plot will give the simulated unsaturated water breakthrough curve.

$$\frac{\partial K_p}{\partial z} + \frac{\partial S_d}{\partial t} = 0 \tag{6}$$

$$C_K = \frac{dK_p}{dS_d} = \alpha\beta S_d^{\beta-1} \tag{7}$$

$$t_{out} = \frac{TL}{C_K} \tag{8}$$

Experimental Results And Discussions

Three laboratory packed sand columns of length 50 cm and diameter 30 cm were studied. One column was filled with sea sand (SS) and the others were with mixed sands of coarse grained river sand (RS) and medium grained sea sand (mixing ratio for MS1was RS:SS = 2:1 and for MS2 was RS:SS =

10:1 by volume). In this paper only the results of MS2 have been shown.

For saturated water breakthrough curve experiment, water was added manually from the top of the sample maintaining just saturation and free drainage from the bottom of the sample was measured. Fig.2 and 3 show the observed saturated water breakthrough curve and the estimated large pore size distribution respectively. We see that MS2 had 4.92% large pores ranging from 78 to 142 μm.

For unsaturated water breakthrough curve experiments, rainfall of constant intensities were applied from the top of sand column using a rainfall simulator. Fig.4 shows the observed and the simulated unsaturated water breakthrough curves for different rainfall intensities. Analysis of the observed data for rainfall intensity of $103*10^{-6}$ *m/sec (R1)* showed that 26% of the total rainfall contributed flow to the 4.92% (large pores) of the total area and came out very fast as bypassing flow. The rest 74% of the total rainfall was stored in the fine pores. Therefore, input *I* to a large pore was 5.3 times the rainfall intensity. Similar observation was found for rainfall intensity of $49.14*10^{-6}$ *m/sec (R2)* where input *I* to a large pore was found to be 5.85 times the rainfall intensity. The simulations presented here are based on these experimental observations. However, the simulations show that there exist lag times between the observed data and the simulation results: the lower is the rainfall intensity the higher is the lag time.

The physical interpretation of the above phenomena is that at the beginning of the rainfall, water will be consumed by the small pores and the large pores will remain empty until the surface of the small pores have become saturated when the excess water will go into the large pores. Thus the flow contributing area of a large pore would be much more larger than the area of the pore itself. This accounts for the multiplication factor in the rainfall intensity to be the input to a large pore. The above interpretation also explains lag time as the difference between the starting time of rainfall and the actual time of inflow into a large pore.

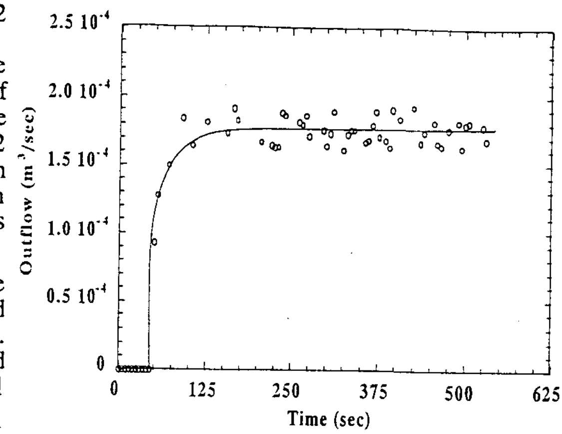

Fig.2 Saturated Water Breakthrough Curve

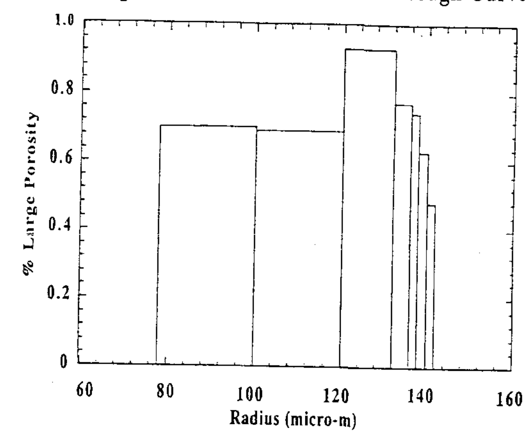

Fig.3 Large Pore Size Distribution

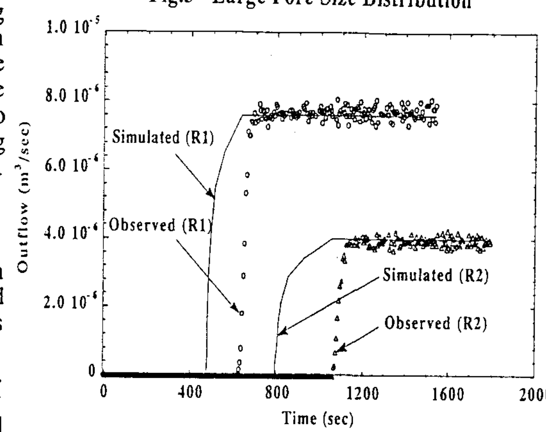

Fig.4 Unsaturated Water Breakthrough Curve
(R1=$103*10^{6}$ m/sec And R2=$49.14*10^{6}$ m/sec)

Conclusions

The mechanism of flow of water through partially saturated large pores in laboratory packed sand columns was studied. Experimental observations showed that more than 25% of the total rainfall was carried out as bypassing flow by about 5% large pores. A kinematic wave model for simulating partially saturated large pore flow is proposed and is verified with observed data. It is seen that the model is capable of predicting the real process of flow although a better model to simulate the lag time phenomena is under investigation.

References

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Radulovich, R., Solorzano, E., and Sollins, P.; Soil Macropore Size Distribution ..., *Soil Sci. Soc. Am. J.*, 53, 556-559, 1989.