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Estimating Soil Wetting Profile under Saturated Infiltration Process by Numerical Inversion Solution in Land Slopes

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Abstract: Soil wetting profile is one of the most important parameters in soil physics that influence on crops growth. The aim of this study is estimating of soil wetting profile in 1 m depth of soil surface under saturated and unsaturated infiltration process. The study has been conducted in loamy soil of Gonbad research station, Hamadan, Iran. Field infiltration experiments were carried out in four tensions including, 0 cm H_2O (using double ring infiltrometer), 6, 9 and 15 cm H_2O (using tension infiltrometer), five slopes including 0-, 10-, 20-, 30- and 40 degree of slope and in 3 replications. Water contents in various soil depth measured using a TDR instrument in different times. Totally 60 water infiltration were carried out. Soil wetting profile extracted using measured data and numerical simulation using Hydrus 2D code. Results indicated that before beginning of infiltration volumetric water content at near the soil surface is less than that of deep soil depth, but after beginning of infiltration volumetric water content at near the soil surface is more than that of deep soil depth. With increase in slope gradient water content values decreased in same soil depth. In low tension moisture distribution were more extended than that of high tension. In all tension treatments relative error and root mean square error between simulated and measured data were calculated less than 3.22% and 0.032 respectively. Therefore inverse numerical simulation has acceptable consistency with measured data.

Key words: Wetting profile • Infiltration • Numerical inversion solution • Sloping lands

INTRODUCTION

Crop net water requirement should be saved in soil porosity and then use by the plant. Infiltration constitutes the base source of water to sustain the growth of plants, is filtered by the soil which removes many contaminants such as physical, chemical and biological contaminant and refills the ground water supply [1, 2]. Water that infiltrated in soil causes the water content increase in soil profile. Amount of water that can be held in soil porosity (that named soil wetting profile) depend on many factors such as soil texture, soil physical, chemical and hydraulic properties, soil surface condition, soil and air temperature, evapotranspiration rate and etc. Skaggs and Khaleel [3] reported that numerical methods allow the scientists to quantify the vertical percolation of water and in analysis of contaminant movement through soil. Comparing with direct methods, numerical solutions are less costly, but they need many various parameters as input parameters. Many researchers reported that land slope affect on soil properties [4-6].

To analyzing the water content changes, Richard's [7] three dimensional water flow equation can be used as follow [8]:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r K \frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K \frac{\partial h}{\partial z}\right) + \frac{\partial K}{\partial z} \qquad (1)$$

where θ the volumetric water is content [$L^3 L^{-3}$], h is the pressure head [L], $K(h)$ is the unsaturated hydraulic conductivity [$L T^{-1}$], r is the radial coordinate and Z is the vertical coordinate with upward positive assumed.

Hydrus 2, 3D used various of hydraulic model to simulate Richard's differential equation, that including Van Genuchten - Mualem [9] model, the van Genuchten - Mualem model with an air-entry value of -2 cm, modified

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van Genuchten type equations model [10], the equations of Brooks and Corey [11], the lognormal distribution model [12] and a dual-porosity model [13]. Equation 1 can be solved numerically for the Warrick's [14] initial and boundary conditions.

Inverse Method: Many direct and indirect methods can be used to predict the unknown parameter [15]. Inverse methods are based on optimization of objective function. The objective function should be minimized during the parameter estimation process can be defined as [16]:

$$f(b,q,p)=\sum_{j=1}^{m_q} V_j \sum_{i=1}^{n_{qj}} W_{ij}\left[q_j^*(x,t_i)-q_j(x,t_i,b)\right]^2 + \sum_{j=1}^{m_p} \overline{V_j} \sum_{i=1}^{n_{pj}} \overline{W_{ij}}\left[p_j^*(q_i)-p_j(q_i,b)\right]^2 + \sum_{j=1}^{n_b} \hat{V}_j\left[b_j^*-b_j\right]^2 \quad (2)$$

where $N(b, q, p)$ is the objective function, m_q is the number of different sets of measurements, n_{qj} is the number of measurements in a particular measurement set. $q^*_j(x, t_i)$ represents specific measurements at time t_i for the j th measurement set at location $x(r,z)$, $q_j(x,t_i,b)$ are the corresponding model predictions for the vector of optimized parameters (2_r, 2_S, ", l, n and K_S). V_j and W_{ij} are weights associated with a particular measurement set or point, respectively. m_p, n_{pj}, $p^*_j(2_i)$, $p_j(2_i,b)$, $\overline{V_j}$ and $\overline{W_{ij}}$ have the similar meaning as mentioned but for the soil hydraulic properties. b^*_j is the prior knowledge of the soil hydraulic parameters and b_j final estimates of soil hydraulic parameters. n_b is the number of parameters with prior knowledge and $\hat{V}_j$ is the pre assigned weights. In the right hand of equation (9), the first term is the differences between the estimated and measured space – time variables, the second term is represents differences between independently measured and predicted soil hydraulic properties and the third term is represents a penalty function for deviations between prior knowledge of the soil hydraulic parameters and their final estimates. Minimization of the objective function $N(b,q,p)$ is accomplished by using the Levenberg-Marquardt nonlinear minimization method [8], which combines the Newton and steepest descend methods, and generates confidence intervals for the optimized parameters. In this research cumulative infiltration data in each slope gradient assumed as $q^*_j(x, t_i)$.

In this study in various times of infiltration process, the volumetric water content in various depths of soil (include 0-20, 20-40, 40-60, 60-80 and 8-100 cm) have been measured using a Time Domain Reflectometry (TDR), also volumetric water content in mentioned depths have been estimated with numerical simulation using Hydrus 2D code for homogeneous loamy soil. Finally the accuracy of inverse numerical solution evaluated by two statistical parameters.

MATERIALS AND METHODS

Study Area: Experiments and study was conducted at Gonbad research station, Hamadan, Iran (48° 42.14' N lat., 34° 41.74' W long. and 2170 m Elev.). Laboratory analysis showed that soil texture in the experimental area is loamy, based on USDA soil textural triangle [17]. Some of soil physical properties such as particle density, bulk density, total porosity and initial water content are listed in Table 1.

Experiments: Five various soil surface slope gradients including 0- , 10- , 20- , 30- , and 40- degree slopes were selected in the area. For each slope gradient, water infiltration experiments were carried out by a double ring and a tension infiltrometer at tensions 0, 6, 9 and 15 cm of water in three replications. Totally 60 water infiltration experiments were carried out in five different surface slopes, four tensions and three replications. A soil profile with 1.5 m length, 1.5 m width and 2 m depth was excavated. Soil layer was homogenous and abrupt changes in soil texture and soil layer were not observed within 2 m of the soil profile. When the amount of water entered into the soil did not change with time for three consecutive measurements taken at 5- minute intervals, steady state flow was assumed and the corresponding infiltration rate was calculated based on the last three measurements. Generally, steady state flow was achieved within 30 to 60 min for the tension infiltrometer and within 60 to 120 min for the double ring infiltrometer. To estimate water content changes in saturated condition, a double ring infiltrometer with inner and outer rings of 0.2 and 0.3 m in diameter, respectively, was used at a constant head (Reynolds *et al*., 2002). To estimate water content changes in unsaturated condition, a tension infiltrometer with a 0.2 m diameter disk (soil measurement systems, Tuscon. Az) was used. At first the location of experiment was selected and then a thin layer ($5\times10^{G3}m$) of moist fine sand was applied over the prepared surface at each measurement location in a circular area with a diameter equal to the diameter of infiltrometer disk. The hydraulic conductivity of testing sand must be more than that of the experimental soil. After preparation of the experiment location, tension infiltrometer instrument was regulated in given tension and was placed on it. The amount of infiltration into the soil was measured by recording the water level falling in the graded reservoir tower as a function of time. The sorptivity coefficient and the saturated and unsaturated hydraulic conductivity values were calculated by Matlab software.

RESULTS AND DISCUSSION

To measure and calculate soil physical properties, for each slope gradient three disturbed and three undisturbed samples (0.05 m in diameter and 0.05 m in height) were taken from areas next to the measurement locations. Some physical properties of experimental soil including bulk and particle density, total porosity percentage and initial water content at the soil surface have been illustrated in Table 1. Bulk density has a regular trend with increase in slope gradient and it is decreased with increase in slope gradient. To running the hydrus 3D code the initial estimate of 2_r, 2_S, ", *n* and K_S estimated with Rosetta Lite program, based on bulk density and sand, silt and clay percentages and l = 0.5. To obtained the optimized unsaturated hydraulic parameters by numerical inversion method, for each slope gradient, Hydrus 3D code run with initial and boundary conditions. The optimized unsaturated hydraulic parameters (2_r, 2_S, ", *l*, *n* and K_S) obtained with Hydrus 3D have been illustrated in Table 2. According to Table 3, with increasing slope gradient, 2_S, K_S and *n* values are decreased, the 2_r values are increased and " and *l* values have irregular changes. Figs 1 to 3 illustrate the soil wetting profile under infiltration process for 0, 20 and 40 degree of slope gradient, obtained by numerical inversion method and measured data. With increase in tension, the falling rate of 2 in 0 degree is more than that of 40 degree of slope gradient. Therefore, by increasing tension, the falling rate of 2 decreased with increase in slope gradient. It can relate to down slope component of each soil particle weight and difference of soil arrangement in two level and sloping lands. With increase in slope gradient from 0 to 40 degree of slope, saturated water content decreased from 34.9 to 32.5 percentage. In steep slopes infiltration rate at early time of experiments is more than that of in low slopes. By time elapsing infiltration rate in steep slopes decreased and infiltration rate decreased to less than that of in low slopes. Therefore in steep slopes amount of water content is less than that of in low slopes at the same soil depth. The relative error (RE) and root mean square error (RMSE) values for various slopes and at different times have been illustrated in Tables 3 and 4 respectively.

In all slopes, before experiments beginning water contents assumed equal to initial water content, therefore values of RE and RMSE will be zero. With time elapsing numerical estimated water content was different than that measured, therefore RE and RMSE values increased with increase in time. Minimum and maximum values of RE for

Table 1: Some selected soil physical and chemical properties of the experimental site

	Slope gradient (degree)				
Parameter	0	10	20	30	40
Bulk density (gr/cm^3)	1.66	1.67	1.68	1.68	1.69
Particle density (gr/cm^3)	2.58	2.57	2.57	2.57	2.58
Porosity (%)	35.66	35.02	34.63	34.63	34.5
Initial water content(-)	0.12	0.122	0.123	0.121	0.123

Table 2: Optimized unsaturated hydraulic parameters (2_r, 2_S, ", *l*, *n* and K_S) obtained by numerical inversion using Hydrus 3D

	Slope gradient (degree)				
Parameter	0	10	20	30	40
$2_r(cm^3/cm^3)$	0.099	0.102	0.107	0.114	0.119
$2_s(cm^3/cm^3)$	0.3488	0.347	0.3365	0.3305	0.3246
"$(1/cm)$	0.0154	0.0151	0.0153	0.0149	0.0147
$n(-)$	1.856	1.775	1.637	1.576	1.469
$K_S(cm / day)$	3.466	3.438	3.402	3.387	3.341
$l(-)$	0.378	0.426	0.398	0.388	0.415

Table 3: values of Relative Error (RE) for different slopes and times

	Slope gradient (%)				
Time (min)	0	10	20	30	40
0	0	0	0	0	0
10	1.1	1.61	1.67	1.85	2.2
30	1.45	1.75	1.83	2.08	2.48
60	2.09	2.15	2.23	2.34	3.03
90	2.21	2.3	2.38	2.56	3.1
120	2.37	2.41	2.49	2.82	3.22

Table 4: Values of Root Mean Square Error (RMSE) for different slopes and times

	Slope gradient (%)				
Time (min)	0	10	20	30	40
0	0	0	0	0	0
10	0.008	0.012	0.013	0.014	0.017
30	0.012	0.015	0.015	0.017	0.02
60	0.019	0.02	0.02	0.021	0.027
90	0.022	0.022	0.023	0.025	0.029
120	0.025	0.025	0.025	0.029	0.032

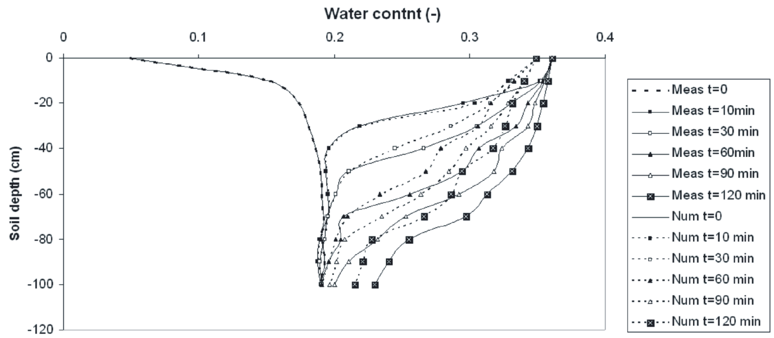

Fig. 1: Measured and numerical solution of wetting profile in 0 degree of slope (level surface)

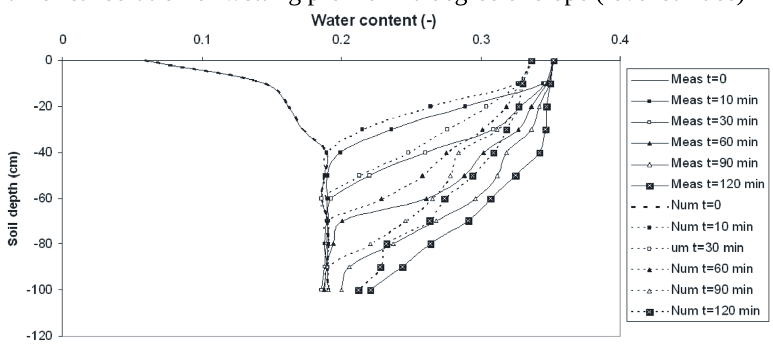

Fig. 2: Measured and numerical solution of wetting profile in 20 degree of slope

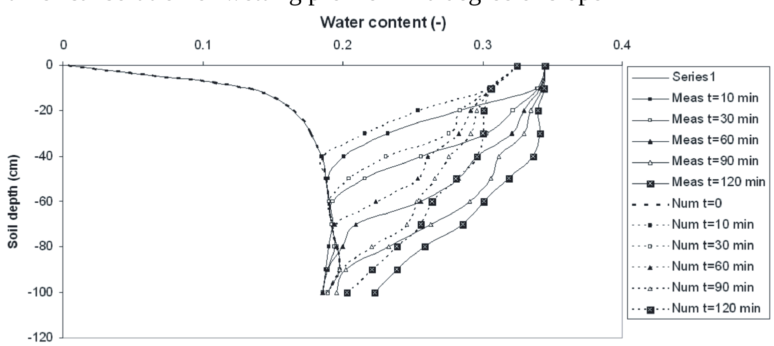

Fig. 3: Measured and numerical solution of wetting profile in 20 degree of slope

different times and slopes are 0 and 3.22%, Also, minimum and maximum values of RMSE for different times and slopes are 0 and 0.032 respectively.

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