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Simulating Water Flow to a Subsurface Drain in a Layered Soil

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Abstract: The objective of the work presented in this paper was to simulate drain flow into subsurface drainage pipes for a layered soil profile using a finite element based HYDRUS-2D model. Data from the drainage experiment in North Central Ohio were used as input to the model. Studies were conducted to determine the ability of the model to predict drain discharge-water table elevation relationships. The model was also used to evaluate the effect of backfill on drain discharge-water table elevation relationships. HYDRUS-2D underpredicted drain discharge compared to the empirical and Kirkham-Hooghoudt equations for water table elevations above 70 cm. However, HYDRUS-2D predictions were very close to those using empirical and Kirkham-Hooghoudt equations for water table elevations below 70 cm. In the backfill simulation scenario with backfill soil saturated hydraulic conductivity values obtained 40 years after the installation of the drains, the model produced higher drain flow rates than those obtained without simulating backfill when the midspace water table elevation was greater than 70 cm, but still underpredicted drain discharge compared to the empirical and Kirkham-Hooghoudt equations. In conclusion, to predict drain flow into a subsurface drain pipe for a layered soil using HYDRUS-2D, the model may give better results with the hydraulic conductivity values of backfill and the model needs more tests for layered soil conditions.

Key Words: Drain discharge, finite element, layered soil, HYDRUS-2D

Katmanlı bir Toprakta Drenaj Borusuna Su Akışının Simulasyonu

Özet: Bu makalede sunulan çalışmanın amacı katmanlı bir toprak profilindeki toprakaltı dren borusuna drenaj suyunun akışını sonlu eleman prensibine dayalı HYDRUS-2D modelini kullanarak simule etmektir. Orta Kuzey Ohio'daki bir drenaj deneme alanına ait veri, modele girdi verisi olarak kullanılmıştır. Modelin dren debisi-su tablası yüksekliği ilişkisini tahmin etmedeki yeterliliği belirlenmeye çalışılmıştır. Model drenaj hendeği dolgusunun dren debisi-su tablası yüksekliği ilişkisine etkisini değerlendirmede de kullanılmıştır. Su tablası yüksekliğinin 70 cm'den büyük olduğu durumlarda, HYDRUS-2D deneysel ve Kirkham-Hooghoudt eşitliklerinden daha düşük bir tahmin yapmıştır. Bununla birlikte, su tablası yüksekliğinin 70 cm'den küçük olduğu durumlarda, HYDRUS-2D tahminleri deneysel ve Kirkham-Hooghoudt eşitlikleriyle tahmin edilen değerlere çok yakındır. Su tablası yüksekliğinin 70 cm'den büyük olduğu zaman ve dren hendeği dolgusunun simulasyonunda drenlerin yerleştirilmesinden 40 yıl sonra ölçülen dolgu hidrolik iletkenlik değerlerinin kullanılmasıyla, dolgunun dikkate alınmamasından daha yüksek dren debileri elde edilmiştir. Sonuç olarak, katmanlı bir toprakta bir drenaj borusuna akan suyu tahmin etmede, HYDRUS-2D modeli dren dolgu toprağının hidrolik iletkenlik değerleriyle daha iyi sonuçlar verebilir ve modelin bu koşullar için daha fazla testi gerekir.

Anahtar Sözcükler: Drenaj debisi, sonlu eleman, katmanlı toprak, HYDRUS-2D

Introduction

There are many water table management models developed to predict drain flows. DRAINMOD and SWATRE are two popular models used in the USA and Europe, respectively. To predict drain flow rates, SWATRE uses a finite difference solution of the Richards equation and DRAINMOD uses the Hooghoudt and Kirkham equations in terms of midspace water table elevation between drains.

Numerical methods are frequently used to solve problems for water flow to drains in a soil profile. The solutions may be based on finite difference, finite element, or some other kinds of boundary approximation techniques. The rate of water movement into drains depends on the hydraulic conductivity of the water flow domain of the surrounding soil, drain spacing and depth, soil profile depth, and water table elevation.

Skaggs (1980) states that water movement to drains can best be quantified by solving the Richards equation for two-dimensional flow. In spite of input and computational time requirements, which in the past have probably prohibited the practical use of these methods, numerical solutions provide a very useful means of evaluating approximate equations that compute drainage flow.

Vimoke et al. (1963) represented the drain tube as a single grid point in their electrical resistance network studies. They compared the drain flows from their networks to analytic solutions of the Kirkham equation. They stated that the network data generally deviate less than 2% if a logarithmic expression is used to calculate network resistance adjacent to the drain.

Merva et al. (1983) developed a finite element model to solve Laplace's equation for a non-homogeneous layered soil. The model predicted the position of the water table for a drainage system in Toledo silty clay. They stated that the water table depth predictions were of an acceptable accuracy. In addition, while modeling the three-layered Hoytville silty clay loam with a trench backfill (as one- layered homogeneous soil), they found that the hydraulic conductivity of the backfill does not seem to affect the critical time (arbitrarily chosen as 30 h) to drop the water table from the surface to 30 cm, and thus, they stated that a very low value of hydraulic conductivity (2.7 to 4.2 times lower than the hydraulic conductivity of the first layer) in the second layer (such as might be found in a plow layer) of a three-layered soil does seriously restrict the permissible drain spacing.

To simulate water movement from a variably saturated soil into a drain pipe, Martinez et al. (1989) used a computer program developed by Kaluarachchi and Parker (1987) to numerically solve the Richards equation. Martinez et al. represented the drain tube as a hole with an effective drain radius. As a boundary condition, they simulated the drain as a seepage face. In the design of the grid, they used rectangular elements for the soil region far from the drain and triangular elements around the drain. They compared the finite element results with measured drain flow data from southeast Indiana. As a result, they stated that the finite element model simulated drain flow hydrographs reasonably well for both 5 and 10 m drain spacings, except that their model underestimated peak flows.

Rogers et al. (1995) used numerical solutions of the Richards equation to derive flow nets and velocity distributions for two shallow soil profiles for saturated flow, steady rainfall seepage, and a case with a falling water table and flow to shallow drains. They simulated the drain as a single node in the mesh by the procedure of Vimoke and Taylor (1962) as modified by Rogers and Fouss (1989). They also used the Hooghoudt equation to calculate the midspace water table elevation for a given drain flow rate and compared it with their numerical results. The predictions with the Hooghoudt equation tended to track the steady state rainfall case, but tended to predict higher drain flow rates for a given midspace water table elevation.

Yu and Konyha (1992) developed a boundary model solution to the Laplace equation to determine flow nets in soils with drainage and subsurface irrigation systems. Their model predicted water table position, and hydraulic head loss at the drain, as well as flux and potential along the boundary. They also indicated that their program could analyze flow problems involving layered soils, trench effects, subsurface irrigation and drainage. Yu and Konyha stated that their model's water table predictions agreed very closely with those predicted using the Hooghoudt equation.

To characterize drain discharge as a function of water table elevation for a homogeneous soil, Salem and Skaggs (1998) used SWMS-2D (Simunek et al., 1994), which solves the Richards equation by using a finite element technique. To evaluate the solution, model results were compared with the results obtained from the Kirkham equation. They stated that the model solution for both drain discharge and pressure head at different locations in the flow domain matched the Kirkham equation solution, with an error not exceeding 5% when the drain radius was small (r = 1 and 5 cm) compared to the problem geometry, and errors up to 20% when the drain effective radius was large (r = 30 cm) in comparison to drain depth or depth to the impermeable layer.

The objective of the work presented in this paper is to simulate drain discharge into subsurface drainage pipes for a layered soil profile using HYDRUS-2D (Simunek et al., 1996).

Materials and Methods

The HYDRUS-2D model was used to determine drain discharge as a function of midspace water table elevation above the drain. The HYDRUS-2D model is the latest commercial version of the SWMS-2D program simulating water flow and solute transport in two- and three-dimensional axisymmetric variably saturated porous media. The model is Microsoft Windows based and supported by an interactive graphics-based interface for data processing, generation of a structured mesh, and graphic presentation of the results. The model includes a mesh generator for unstructured finite element grids, MESGEN-2D.

The HYDRUS-2D model numerically solves the Richards equation for saturated and unsaturated water flow to drains. The modified form of the Richards equation used in the model is

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial x_i} K\,[(K^A_{ij}\frac{\partial h}{\partial x_i} + K^A_{iz})] - S \qquad \text{[Eq.1]}$$

where Θ is the volumetric water content (L3L-3), h is the pressure head (L), S is a sink term (T-1), xi is a spatial coordinate (L), t is time (T), KijA is a component of a dimensionless anisotropy tensor KA, and K is the unsaturated hydraulic conductivity function (LT-1). Subscripts i and j represent two directions, x (horizontal coordinate) and z (vertical coordinate).

Data from the drainage experiment of Schwab et al. (1963) in North Central Ohio were used as input to the model. The soil domain with the drain is represented similarly to that presented by Salem and Skaggs (1998). For the subsurface drainage system at this research site, the drain spacing was 12.2 m and the drain depth was 90 cm. The soil profile depth (165 cm) simulated by Skaggs et al. (1981) was used in this study.

The HYDRUS-2D model was used to develop drain discharge-water table elevation curves to be compared with two curves: i) obtained using the empirical equation by Hoffman (1963) transformed to metric units:

$$\text{LogQ} = \frac{H^2}{1935.42} - \frac{H}{56.44} - 1.865 \qquad \text{[Eq. 2]}$$

where Q is the drain discharge (cm/day), and H is the midspace water table elevation (cm) above the drain; and ii) obtained using the Kirkham and Hooghoudt equations as used in DRAINMOD (Skaggs, 1980). The English unit version of Eq. 2 was found to be the best empirical solution by Hoffman (1963) using the experimental data from the site. This equation was developed using the measured midspace water table elevations above the drain and the corresponding drain discharges for the years 1960, 1961, and 1962. Therefore, an assumption was made that Eq. 2 best describes the drain discharge-water table elevation relationship.

The drain in Figure 1 was represented as a completely permeable half circle (EFG) with a radius equal to the effective radius (0.48 cm) of the drain. The upper boundary AB was represented as Neuman-type constant flux (evapotranspiration rates between 0 and 0.3 cm/day) and constant pressure (0.1 cm) boundaries. The boundaries BC, CD, DE, and GA were represented as no flow boundaries. The boundary represented by the drain (EFG) was considered as a seepage face.

The HYDRUS-2D model needs the following input data: number of layers in the soil profile, initial water table depth, residual and saturated water contents of each soil layer, parameters of α and n (the coefficient and the exponent in the soil water retention function, respectively), saturated hydraulic conductivity of each soil layer, root water uptake parameters and root distribution in the soil profile. The Table lists some of these input data. The residual water content, and the parameters a and n in the soil water retention curves were obtained using the RETC program (Van Genuchten et al., 1991) with the soil water retention data from Skaggs et al. (1981). A 40 cm corn root depth at the middle of growing season was also assumed and used as the root distribution depth. For all HYDRUS-2D simulations, it was assumed that the initial water table was ponded on the surface (0.1 cm).

To evaluate the effect of backfill on drain discharge and on the shape of the drain discharge-water table elevation curve, the backfill was divided into five layers with the depths given in the Table. All the input values used for the soil layers except K_{sat} values were also used for the layers of backfill. Forty years after the installation of the drains at the site, soil samples from the backfill at different depths were collected and analyzed for K_{sat}. The measured saturated hydraulic conductivity values with their corresponding soil sample depths are given in the Table along with the original core data from Schwab et al. (1963).

Results and Discussion

The conceptual system without backfill conditions presented in Figure 1 was simulated using HYDRUS-2D. Figure 2* illustrates the drain discharge-water table

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* The unit of drain discharge (cm^2/h) is for per unit length of lateral.

Table 1. Saturated soil water contents (Θ_s), coefficient a and exponent n for the soil water retention function, and saturated hydraulic conductivity (K_{sat}) for the soil and backfill layers of Toledo silty clay.

							Backfill	
Horizon	Depth$^{\#}$ (cm)	Θ_s (cm^3/cm^3)	Θ_r (cm^3/cm^3)	α (1/cm)	n	$K_{sat}{}^{\#}$ (cm/h)	Depth$^{\sim}$ (cm)	$K_{sat}{}^{+}$ (cm/h)
A_p	0-20	0.536	0.119	0.0044	1.1837	2.540	0-33	1.541
B_1	20-33	0.536	0.119	0.0044	1.1837	0.296	33-46	0.016
B_{21}	33-51	0.536	0.119	0.0044	1.1837	0.138	46-61	0.063
B_{22}	51-76	0.470	0.135	0.0032	1.1252	0.095	61-75	0.193
B_{23}	76-96	0.470	0.135	0.0032	1.1252	0.169	75-96	0.307
C_{11}	96-127	0.470	0.135	0.0032	1.1252	0.01*		
C_{12}	127-165	0.470	0.135	0.0032	1.1252	0.01*		

* From Skaggs et al. (1981)

\# The soil layers depth and hydraulic conductivity data were taken from Schwab et al., (1963).

\+ Core samples were collected from the trench backfill in 1998, 40 years after drain installation.

~ Depths for backfill layers.

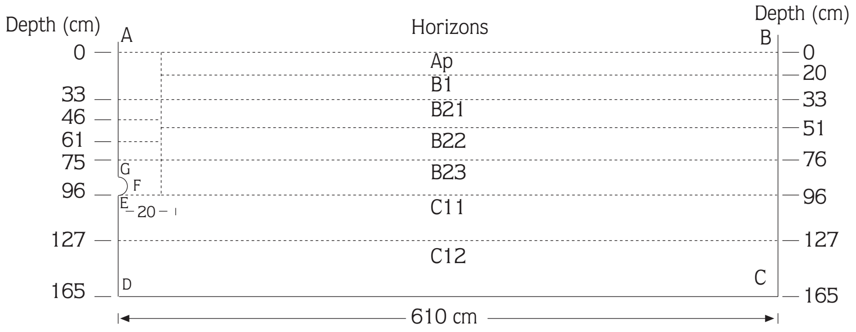

Figure 1. Soil layers used with the HYDRUS-2D model for backfill and for one-half of the drain spacing domain (not to scale) for Toledo silty clay North Central Ohio.

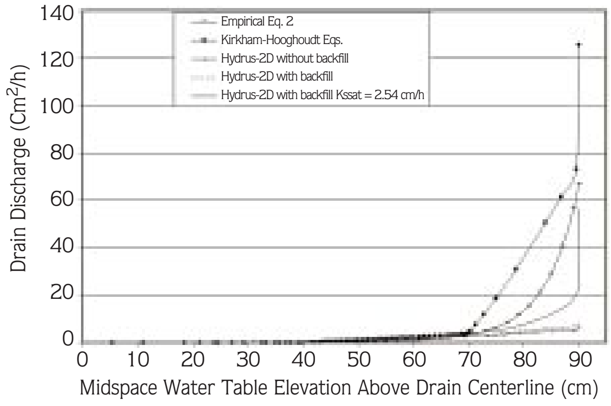

Figure 2. Drain discharge-water table elevation relationship using HYDRUS-2D with/without backfill condition and with all backfill Ksat values equal to 2.54 cm/h compared to those using empirical Eq. 2 and the Kirkham-Hooghoudt equations for Toledo silty clay soil.

elevation relationships for three prediction methods. HYDRUS-2D underpredicted drain discharge compared to Eq. 2 and the Kirkham-Hooghoudt equations for water table elevations above 70 cm. This is mainly because of the very small contribution of drainage water from the first soil layer during early time periods. Maybe for this reason, Merva et al. (1983) reached their result indicating that a very low value of hydraulic conductivity in the second layer seriously restricted the permissible drain spacing. However, after the water table elevation decreased by approximately 20 cm, HYDRUS-2D predictions were very close to those using Eq. 2 and the Kirkham-Hooghoudt equations.

Figures 3 and 4 show the spatial distribution of pressure heads and velocity vectors respectively when midspace water table elevation above the drain centerline is at 87 cm. In Figure 3, the isolines of the pressure head

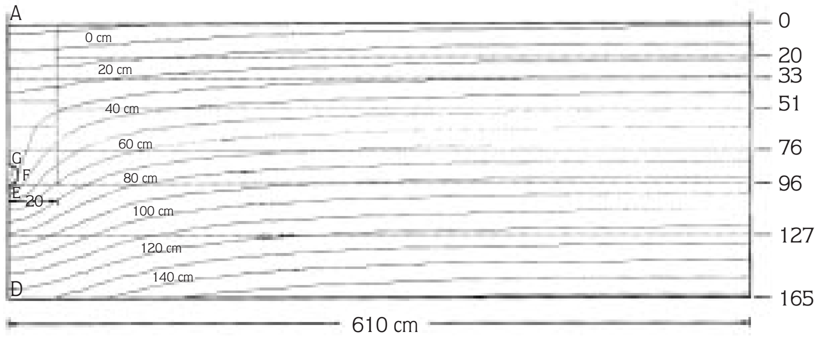

Figure 3. Spatial distribution of pressure head (cm of water) at one-half of the drain spacing for Toledo silty clay soil profile domain when midspace water table elevation above the drain centerline is at 87 cm. The curves of 0 cm pressure heads show water table locations.

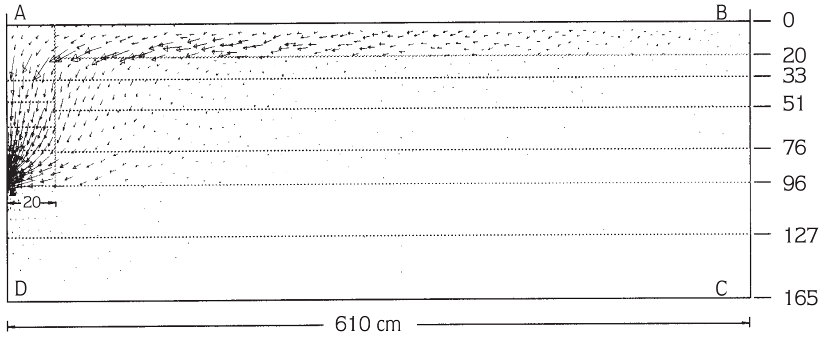

Figure 4. Spatial distribution of velocity vectors for one-half drain spacing for the Toledo silty clay soil profile domain when the midspace water table elevation above the drain centerline is at 87 cm.

in the top layer are almost flat, suggesting that subsurface drainage had almost did no effect on water loss from this layer to the drain tube. In addition, Figure 4 shows that most of the water in the top layer tends to flow horizontally along this layer until it reaches a point over the drain, where the flow direction becomes vertical. These results could be anticipated since the ratio of the hydraulic conductivity of the top layer to the second layer (2.540/0.296 cm/h) was 8.6. Fausey (1977) states that whenever this ratio reaches a value of 5, the interface of these two layers serves effectively as an impermeable boundary for saturated flow. Therefore, the water in the top soil layer does not move vertically to the second layer rapidly, and subsequently water flow in the top layer will be horizontal until it reaches a point over the drain.

Most water flow from the top layer to the second layer occurs through the short interface distance between the top and second layer in the region just above the drain (Fig. 4). The effect of a reworked ditch or backfill at this short interface distance possibly helps provide a better hydraulic connector between the drain and the shallow soil layers. For this reason, HYDRUS-2D was used to simulate backfill in the soil profile domain in the next case.

The drainage system installed in 1958 at this site was trenched and the blinding was the original excavated material. Schwab et al. (1963) stated that the topsoil included alfalfa stems and roots and was placed about 15.2 cm above the top of the concrete tile. Initially to simulate the backfill, the saturated hydraulic conductivity values for the backfill soil layers given in the Table were used in HYDRUS-2D. The resulting drain discharge-midspace water table elevation curve is also given in Figure 2. There is little difference between the HYDRUS-2D curves given in Figure 2 for the no backfill simulation and backfill simulation. In the backfill simulation scenario, the model produced slightly higher drain discharges than those obtained without simulating backfill when the midspace water table elevation was greater than 70 cm. However, the large difference between the curves from HYDRUS-2D and the curves from Equation 2 and the Kirkham-Hooghoudt equations remain when midspace water table elevation is greater than 70 cm. For backfill layers, note that the ratio of saturated hydraulic conductivity of the top layer to the second layer is much greater than 5 (96.3), and therefore the same interface problem discussed earlier was intensified here for the backfill. From this analysis, it appears that more than 40 years after the installation of drains, the backfill is not performing the hydraulic connector function between the upper soil layers in the backfill and the drain tube.

Taylor and Fausey (1982) stated that on a long-term basis the drainage of clay soils is always inadequate. Their results on Toledo silty clay indicated that the trenched and backfilled condition helped increase drain flow rates by as much as 100 to 200% compared to drains with no backfill alteration. They also stated that the greater flow rates for the backfilled drains persisted for 4 years after installation; however, a small but consistent decline in flow rate appeared for the last 3 years. This decrease in drain flow probably resulted from soil consolidation, and subsequently a decrease in saturated hydraulic conductivity in the backfill. Trafford and Rycroft (1974) stated that changes in saturated hydraulic conductivity depend on the initial working conditions, the stability degree of the soil to water, climatic regimes and other factors.

To further evaluate the backfill effect, a range of saturated hydraulic conductivity values among the values given in the Table were assigned to the backfill layers, using the maximum saturated hydraulic conductivity value of 2.54 cm/h (undisturbed value of top soil layer) as an upper limit for each layer. A number of combinations were evaluated. Overall, the best HYDRUS-2D curve was obtained when a Ksat value of 2.54 cm/h was used for all the backfill soil layers. This curve, shown also in Figure 2, again illustrates how well HYDRUS-2D produces drain flow results that match those of Equation 2 and the Kirkham-Hooghoudt equations for all midspace water table elevations below 70 cm. At water table elevations greater than 70 cm, there is substantial improvement over the other HYDRUS-2D results shown in Figure 2. With this curve, in the range of water table elevations from 70 to 90 cm, the Kirkham-Hooghoudt equations overpredict drain flow by 82% and HYDRUS-2D underpredicts by 52% with reference to Eq. 2.

Within the scope of the analyses presented above and the available data, the objective was met as discussed above. The curves in Figure 2 illustrate the capability of using HYDRUS-2D to predict drain flows. No specific limitations in model capability were found. However, there were limitations in model application because of the lack of appropriate measured hydraulic conductivity of backfill as input data for the model.

Conclusions

The objective of the work presented in this study was to simulate drain flow into subsurface drainage pipes for a layered soil profile using HYDRUS-2D. The drain was represented as a completely permeable half circle with a radius equal to the effective radius of the drain. Data from the drainage experiment in North Central Ohio were used as input to the model.

HYDRUS-2D underpredicted drain flow compared to the empirical and Kirkham-Hooghoudt equations for water table elevations above 70 cm. However, HYDRUS-2D predictions were very close to those using the empirical and Kirkham-Hooghoudt equations for water table elevations below 70 cm.

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