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Numerical Modeling of Water Movement from Buried Vertical Ceramic Pipes through Soils

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ABSTRACT

The problem of water scarcity is becoming common in many parts of the world, to overcome part of this problem proper management of water and an efficient irrigation system are needed. Irrigation with a buried vertical ceramic pipe is known as a very effective in the management of irrigation water. The two- dimensional transient flow of water from a buried vertical ceramic pipe through homogenous porous media is simulated numerically using the HYDRUS/2D software. Different values of pipe lengths and hydraulic conductivity were selected. In addition, different values of initial volumetric soil water content were assumed in this simulation as initial conditions. Different values of the applied head were assumed in this simulation as boundary conditions. The results of this research showed that greater spreading occurs in the horizontal direction. Increasing applied heads, initial soil water contents and pipe hydraulic conductivities, cause increasing the size of wetting patterns but in a few increases. Also, the results showed that the empirical formulas which can be used for expressing the wetted width and depth in terms of applied head, initial soil water content, application time, pipe hydraulic conductivity, and pipe length, are good and can be used as design equations.

Key words: numerical modeling, soil water content, wetting patterns, HYDRUS.

نموذج عددي لحركة الماء من أنابيب سيراميك مدفونة بشكل عمودي خلال الترب

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الخلاصة

أصبحت مشكلة ندرة المياه شائعة في العديد من أنحاء العالم. يتطلب إدارة صحيحة للمياه وأنظمة ري كفوءة للتغلب على جزء من هذه المشكلة. ان الري باستخدام أنابيب سيراميك مدفونة بشكل عمودي معروف بانه فعال جدا في إدارة مياه الري. تم محاكاة الجريان الانتقالي الثنائي البعد للماء من أنبوب سيراميك مدفون بشكل عمودي خلال الوسط المسامي المتجانس عدديا وذلك باستخدام برنامج هايدرس ذات البعد الثنائي. تم اختيار قيم مختلفة من أطوال وايصالية هيدروليكية للأنبوب. وبالإضافة لذلك فقد تم اختيار قيم مختلفة للمحتوى الرطوبي الابتدائي الحجمي للتربة كشروط ابتدائية في هذه المحاكاة. تم افتراض قيم مختلفة من الضغط المسلط في المحاكاة باعتبارها شروط محددة. أظهرت نتائج هذا البحث إن اكبر انتشار يحدث في الاتجاه الأفقي. وعند زيادة الضغوط المسلطة، المحتويات الرطوبية الابتدائية للتربة والايصاليات الهيدروليكية للأنبوب فان ذلك سوف يسبب زيادة حجم أنماط الترطيب ولكن هذه الزيادة تكون قليلة. كما أظهرت النتائج إن المعادلات الوضعية التي يمكن استخدامها للتعبير عن عرض وعمق الابتلال بدلالة الضغط المسلط، المحتوى الرطوبي الابتدائي للتربة، وقت الإرواء، الايصالية الهيدروليكية للأنبوب، وطول الأنبوب جيدة ويمكن استخدامها كمعادلات تصميمية.

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1. INTRODUCTION

Subsurface irrigation is one of the most methods perfectly suited for a specific amount of water and applied directly to the root zone, and thus reduce the losses resulting from the evaporation, conveyance, and deep percolation. Some media that are used to transport water for irrigation under the surface, including pots, porous clay pipes, and plastic drip lines with emitters where water leaks or penetrates into the soil, thus increasing the moisture content in the soil. Irrigation systems below the soil surface are becoming increasingly public, since making better water use efficiency for agriculture is very significant in many parts of the world that have limited water resource. This method of irrigation, in some arid and semi-arid regions of the world, has been used with great success. Irrigation with buried vertical ceramic pipe is analogous to drip irrigation since water leaks out from ceramic pipe and wets the surrounding soil along the length of the pipe. Several studied have been conducted on subsurface ceramic pipe systems. **Bainbridge, 2001,** stated that irrigation by buried clay pot is an ideal, well-suited, and well-known for small-scale farms in different parts of the world. This type of irrigation gives ten times better than traditional surface irrigation also better than systems of drip irrigation. Clay pot irrigation is efficient in difficult conditions of limited water resources, high salinity, and limited supply of water. **Ashrafi, et al., 2002,** investigated the relations between the physical and hydraulic parameters in subsurface irrigation such spacing between lateral, depth of installation, time of irrigation, pipe hydraulic conductivity, and the hydraulic head. A numerical model was used for simulating infiltration through porous pipe. The results indicated that the wetted area was affected to the depth of installation and the water applied volume, and an inverse relation between the depth of installation and the lateral spacing of porous clay pipe. **Qiaosheng, et al., 2007,** studied and tested the porous clay pipe in the greenhouse. They developed a simple analytical model by using a dimensional analysis method to simulate the wetted soil shape under porous pipe. The statistical analyses were used to find the accuracy of the work. **Akhoond** and **Golabi, 2008,** tested a new form of vertical installation instead of horizontal installation of the porous clay pipe. The system has been designed for three pipes lengths that were 30, 45 and 60 cm and three water heads 3, 4, and 6 m with an operation time of 300 minutes. The results showed that maximum soil moisture vertical expansion occurred at maximum pressure head of 6m that was equal to double length of the pipe. **Siyal** and **Skaggs, 2009,** conducted experiments with 40 cm pipes lengths made of clay soil, with hydraulic heads of 25, 50, 100 and 200 cm, and with 5 days operation time on various soil textures. Experimental results showed that increasing the applied head of the system increased the size of the wetting pattern, and the depth of installation has a large effect on the recommended horizontal spacing and the amount of evaporation loss. **Siyal, et al., 2009,** concluded that irrigation with pitcher is one of the most efficient systems. Three different size pitcher namely as large of 20 L, medium of 15 L, and small of 11 L that were buried in a sandy loam soil. They showed that for the small pitcher that has half size of the larger pitcher, but with twice hydraulic conductivity produces nearby the same wetting patterns as the largest one. **Khan, et al., 2015,** used Negative Pressure Difference Irrigation (NPDI) which is a type of subsurface irrigation. Experimental work was done by using six porous pipes with different dimensions installed vertically, at a negative pressure of 3 cm, and for four hours as supplied water. Experimental results showed that the wetting pattern of the soil is different for each kind of porous pipes, and the maximum expansion in a vertical and a radial direction vary with the change in length and diameter of the pipes.

The objectives of present study are to develop a numerical model by using the HYDRUS/2D software for simulating the soil water distribution through different soils, Silty Loam, Clay Loam, Silt, Clay, and Silty Clay Loam at various application heads and using ceramic pipes with different lengths and hydraulic conductivities, and to obtain an empirical formula describing the wetted soil width and depth as a function of operating time, pipe hydraulic conductivity, pipe length, applied head, and initial soil water content.

2. WATER FLOW EQUATION

The basic theory describes the flow of fluid in porous media was introduced in 1907 by Buckingham who identified that flow of water through unsaturated soils are extremely dependent upon water content. In 1931 Richard applied continuity equation to the law of Buckingham which represents an extension to Darcy law. The Richards' equation for a two- dimensional isotropic medium, **Abid, 2006, 2012**:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}[K(h)\frac{\partial h}{\partial x}] + \frac{\partial}{\partial Z}[K(h)\frac{\partial h}{\partial Z}] + \frac{\partial K(h)}{\partial Z} \quad (1)$$

where:

θ = volumetric soil water content, cm^3/cm^3,

t = time, *hr*, and

$K(h)$ = soil water conductivity which depend upon pressure head, *cm/hr*,

The solution of equation (1) requires initial and boundary condition. The initial conditions are the dependent variables values which specify inside the domain of flow while the boundary conditions specified either the liquid flux along the boundary, the total potential across the boundary, or gathering of specified flux and head. **Fig. 1** show a typical section of the flow medium considered for a study that consists of two types of cells with various properties. The first type of cells is the pipe body *HGFEH*, while the second type is the cells that belong the soil outside the pipe body *ABCDEFGHA.*

2.1 Assumptions

The main assumptions of this research were, the soil is homogeneous and isotropic, the initial water contents of soils are distributed in regular form through the soils, neglect the soil surface evaporation during application of water, and the wall of the buried vertical ceramic pipe is saturated.

2.2 Initial and Boundary Conditions

The initial conditions were:

$$\theta(x, z, 0) = \theta_i \quad \text{on } ABCDEFGHA \quad (2)$$

The boundary conditions are defined as:

$$\left(\frac{\partial h}{\partial z}\right) = 0 \quad \text{no flux boundaries along } AB, HG \quad (3)$$

$\left(\frac{\partial h}{\partial x}\right) = 0$ no flux boundaries along *AH, ED, BC* (4)

$h(x, z, t) = h_p$ variable heads at the pipe lines *GF, FE* (5)

$h(x, d, t) = 0$ free drainage at bottom of the soil, *CD* (6)

where:

d = depth of the lowest boundary at bottom of the soil.

2.3 Numerical Simulations

Soil hydraulic properties were modeled by using the van Genuchten relationships, **Van Genuchten, 1980**, which are:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (7)$$

$$K(h) = K\, S_e^{\,l}\left[1 - (1 - S_e^{1/m})^m\right]^2 \quad (8)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (9)$$

$$m = 1 - 1/\,n \quad (10)$$

2.4 Input Data

The wetting patterns from the buried vertical ceramic pipe are simulated by using five types of fine soils, Silty Loam, Clay Loam, Silt, Clay, and Silty Clay Loam, through soil classification of United States Department of Agriculture, (USDA). The initial water contents of the soil enclose between residual and saturated water contents which differ in each soil as shown in **Table 1**. Heads that applied at the soil surface differ according to soil type which illustrated in **Table 2**, the minimum applied head was 25cm while the maximum applied head was 200 cm, in each head 10 cm was added as a buried depth of the ceramic pipe. The hydraulic conductivities of the buried vertical ceramic pipe varied in fine soils also according to soil type that shown in **Table 3**, the minimum pipe hydraulic conductivity was 0.0001 cm/hr while the maximum pipe hydraulic conductivity was 0.005 cm/hr.

3. RESULTS AND ANALYSIS

3.1. Wetting patterns

The HYDRUS/2D software was used to predict the soil wetting patterns under several boundary conditions. The simulation of wetting patterns was carried out at the right side because of symmetry for the wetting patterns. The ceramic pipe located at 10 cm below the upper boundary on the left side of the rectangular domain, 1.5cm wide, and with different pipes lengths (10, 20, 30, 40, and 50 cm). **Fig.2** show sample of simulations in different types of soils with a different domain, while **Fig.3** through **Fig.6** shows the effects of the applied head, initial soil water content, pipe hydraulic conductivity, and pipe length respectively in silt soil. Increasing the applied head increased the size of wetting dimensions in horizontal and vertical direction due to an increase of water flux from the wall of the ceramic pipe. Initial soil water contents have few effects on wetting patterns. In general, greater horizontal spreading occurs in fine soil.

3.2 The empirical formulas

STATISTICA software version 10 was used to develop formulas to predict wetted width and depth for each soil texture. This program works with a multiple regression analysis. In each type of soil, numerous data were obtained from HYDRUS/2D, about 7500 value for maximum wetted width and 7500 value for maximum wetted depth or about 4375 value depending upon operating time. The obtained data were gathered in the STATISTICA software that was operating time, the maximum wetted width, the maximum wetted depth, pipe hydraulic conductivities, pipe lengths, applied heads, and initial soil water contents as an input data. **Table 4** and **Table 5** show the empirical formulas of wetted width and depth.

3.3 Statistical analysis

Three statistical parameters, root mean square error (RMSE), mean absolute percentage error (MAPE), and coefficient of determination (R^2) are used to test the discrepancy between the results obtained from HYDRUS and the results obtained from the empirical formulas. These parameters are defined as **Willmott, 1982**:

a- Root mean square error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(M_i - S_i)^2}{N}} \quad (11)$$

b- Mean absolute percentage error (MAPE)

$$MAPE = \frac{1}{N}\sum\frac{(M_i - S_i)}{M_i} * 100 \quad (12)$$

c- Coefficient of determination (R^2)

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(M_i - S_i)^2}{\sum_{i=1}^{N}(M_i - \bar{M})^2} \quad (13)$$

where:

M_i = measured wetted dimensions obtained from HYDRUS/2D, *cm*,
S_i = calculated wetted dimensions by using the empirical formula, *cm*,
N = total number of data, and
$\bar{M}$ = mean values of measured wetted dimensions obtained from HYDRUS/2D, *cm.*

The statistical comparison between wetting pattern sizes (width and depth) obtained by using HYDRUS/2D and those predicted by the empirical formulas are shown in **Table 6** and **Table 7**. From the results for both the wetted width and depth, the maximum value of mean absolute percentage error does not exceed 7%. The RMSE values varied in both direction from 0.3 to 3.68 cm, and a minimum value of the coefficient of determination was 96 % which indicate that the empirical formulas that were used to predict the width and depth of wetted soils can be used with a good accuracy.

4. CONCLUSIONS

The method of subsurface irrigation is becoming increasingly popular especially in developed nations. The subsurface irrigation system was designed for five lengths of ceramic pipe (10, 20, 30, 40, and 50 cm) with five water heads and for various times of irrigation in different soil textures, Silty Loam, Clay Loam, Silt, Clay, and Silty Clay Loam. The results obtained from the simulations show that for a given soil texture, the wetting patterns are sensitive to the applied head, initial soil water content, pipe length and pipe hydraulic conductivity. Increasing the applied head of the system increased the size of wetting patterns. The initial soil water contents and pipe hydraulic conductivities affected the shape of wetted zone only minimally. The maximum horizontal and vertical expansions vary with change in the length of ceramic pipes. In general, the wetting patterns in fine soils extend horizontally much more than the vertical direction**.** The empirical formulas for wetted width and depth can be used as designed equations.

5. REFERENCES

- Abid, M. B., 2006, *Analytical Solution of Unsaturated Soil Water Flow from a Point Source*, Ph.D. thesis, Department of Water Resources Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq.
- Abid, M. B., Hamad, S. N., and Hussain, S. M., 2012, *Analytical Solution of Unsaturated Soil Water Flow from a Point Source*, Journal of Engineering, vol.18, No.1, PP.95-106.
- Akhoond-Ali, A. M., and Golabi, M., 2008, *Subsurface Porous Pipe Irrigation with Vertical Option as a Suitable Irrigation Method for Light Soil,* Asain J. of Scientific Research, vol.1, no.3, pp.180-192.
- Ashrafi, S., Gupta, A. D., Babel, M. S., Izumi, N. and Loof, R., 2002, *Simulation of Infiltration from Porous Clay Pipe in Subsurface Irrigation*, Hydrological Sciences Journal, vol.47, no.2, pp.253-268.
- Bainbridge, D. A., 2001, *Buried Clay Pot Irrigation: a Little Known but Very Efficient Traditional Method of Irrigation,* Agric. Water Manage, vol.48, no.2, pp.79-88.
- Khan, N. N., Islam, M. M., Islam, S., and Moniruzzaman, S. M., 2015, *Effect of Porous Pipe Characteristics of Soil Wetting Pattern in a Negative Pressure Difference Irrigation System*, American Journal of Engineering Research (AJER), vol.4, no.2, pp.01-12.
- Qiaosheng, S., Zuoxin, L., Zhenying, W., and Haijun, L., 2007, *Simulation of the Soil Wetting Shape under Porous Pipe Sub-Irrigation Using Dimensional Analysis,* Irrig. Drain. vol.56, pp.389-398.
- Siyal, A. A., Van Genuchten, M. T., and Skaggs, T. H., 2009, *Performance of Pitcher Irrigation System,* Soil SCI, vol.174, no.6, pp.312-320.
- Siyal, A. A., and Skaggs, T. H., 2009, *Measured and Simulated Soil Wetting Patterns under Porous Clay Pipe Sub-Surface Irrigation,* Agricultural Water Management, vol.96, pp.893-904.
- Van Genuchten, M. Th., 1980, *A closed-form equation for predicting the hydraulic conductivity of unsaturated soils*. Soil Sci. Soc. Amer. J., vol. 44, pp. 892-898.
- Willmott, C. J., 1982, *some comments on the evaluation of model performance*. Bulletin of the American Meteorological Society, vol. 63, no. 11, pp. 1309-1313.

6. NOMENCLATURE

h = pressure head, *cm*,
K = unsaturated hydraulic conductivity of soil, *cm/hr*,
K_s = saturated hydraulic conductivity of the ceramic pipe, *cm/hr*,
L = length of ceramic pipe, *cm*,
l = pore conductivity parameter, dimensionless,
n = pore size distribution index, dimensionless,
t = time, *hr*,
x = wetted width, *cm*,
z = wetted depth, *cm*,
α = inverse of the air entry value, cm^{-1},
θ = volumetric soil water content, cm^3/cm^3,
θ_i = initial soil water content, cm^3/cm^3,
θ_r = residual water content, cm^3/cm^3,
θ_s = saturated water content, cm^3/cm^3.

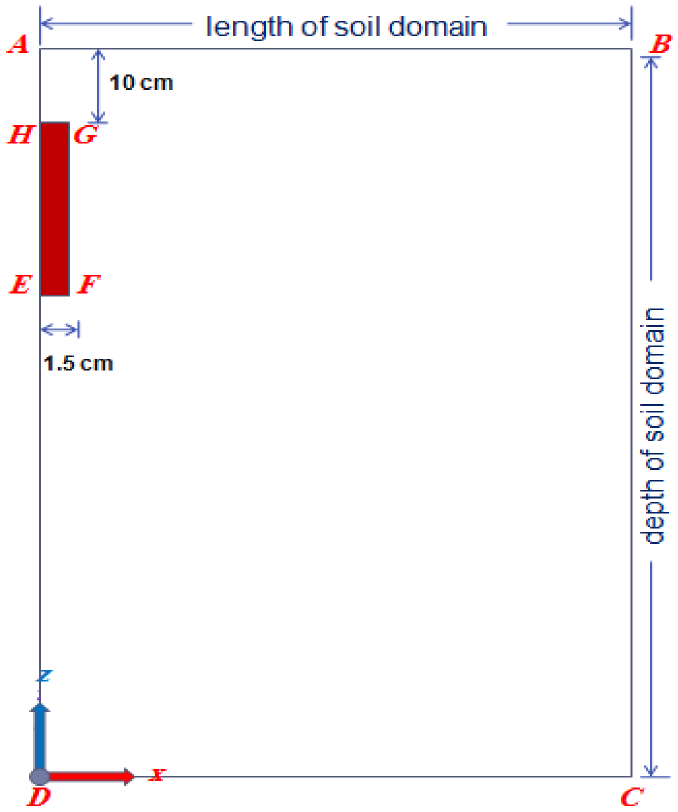
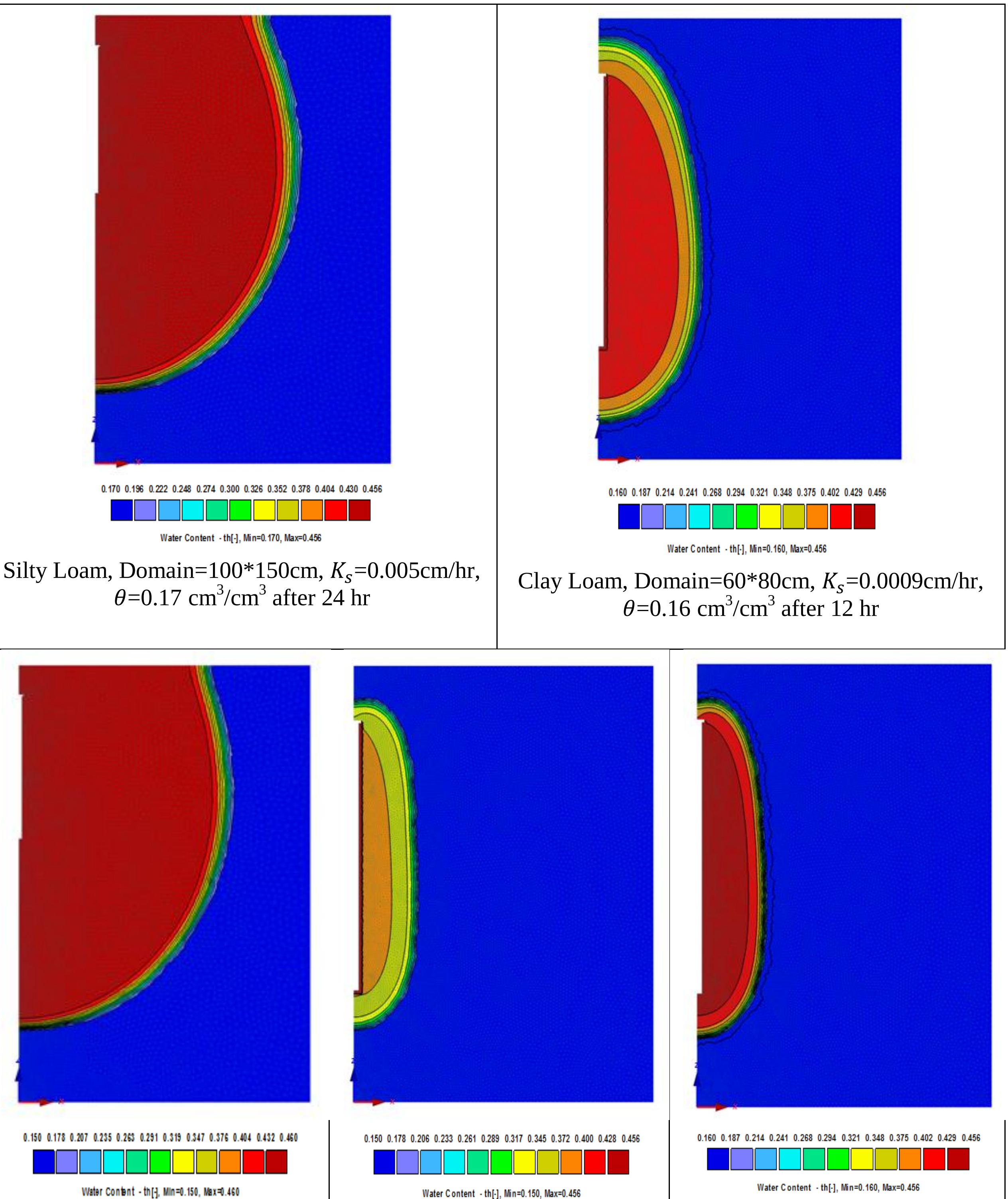


Figure 1. A typical section of the flow medium considered for study.



Silty Loam, Domain=100*150cm, K_s=0.005cm/hr, θ=0.17 cm^3/cm^3 after 24 hr

Clay Loam, Domain=60*80cm, K_s=0.0009cm/hr, θ=0.16 cm^3/cm^3 after 12 hr

Silt, Domain=100*150cm, K_s=0.005cm/hr, θ=0.15 cm^3/cm^3 after 36 hr

Clay, Domain=60*80cm, K_s=0.00012cm/hr, θ=0.15 cm^3/cm^3 after 36 hr.

Silty Clay Loam, Domain=60*80cm, K_s=0.0006cm/hr, θ=0.16 cm^3/cm^3 after 12 hr.

Figure 2. Simulation of wetting patterns from a ceramic pipe in different types of soils with pipe length of 50 cm, applied head of 200 cm, and after different operating times.

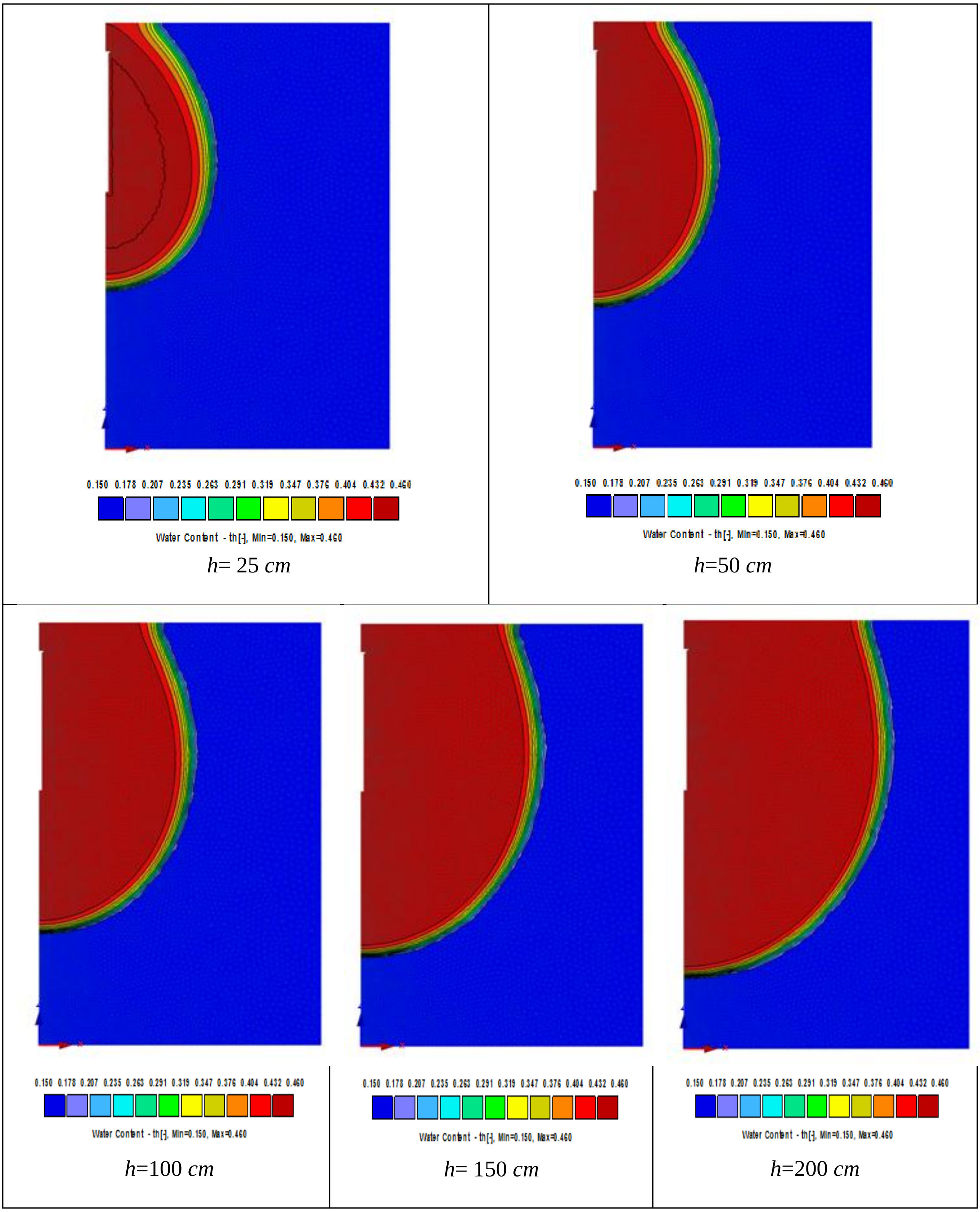


Figure 3. Simulation of wetting patterns from a ceramic pipe in silt soil with 1.0 x1.5 m domain, pipe length= 50 cm, pipe hydraulic conductivity= 0.005 cm/hr, initial soil water content= 0.15 cm^3/cm^3, and with different applied heads after 36 hr.

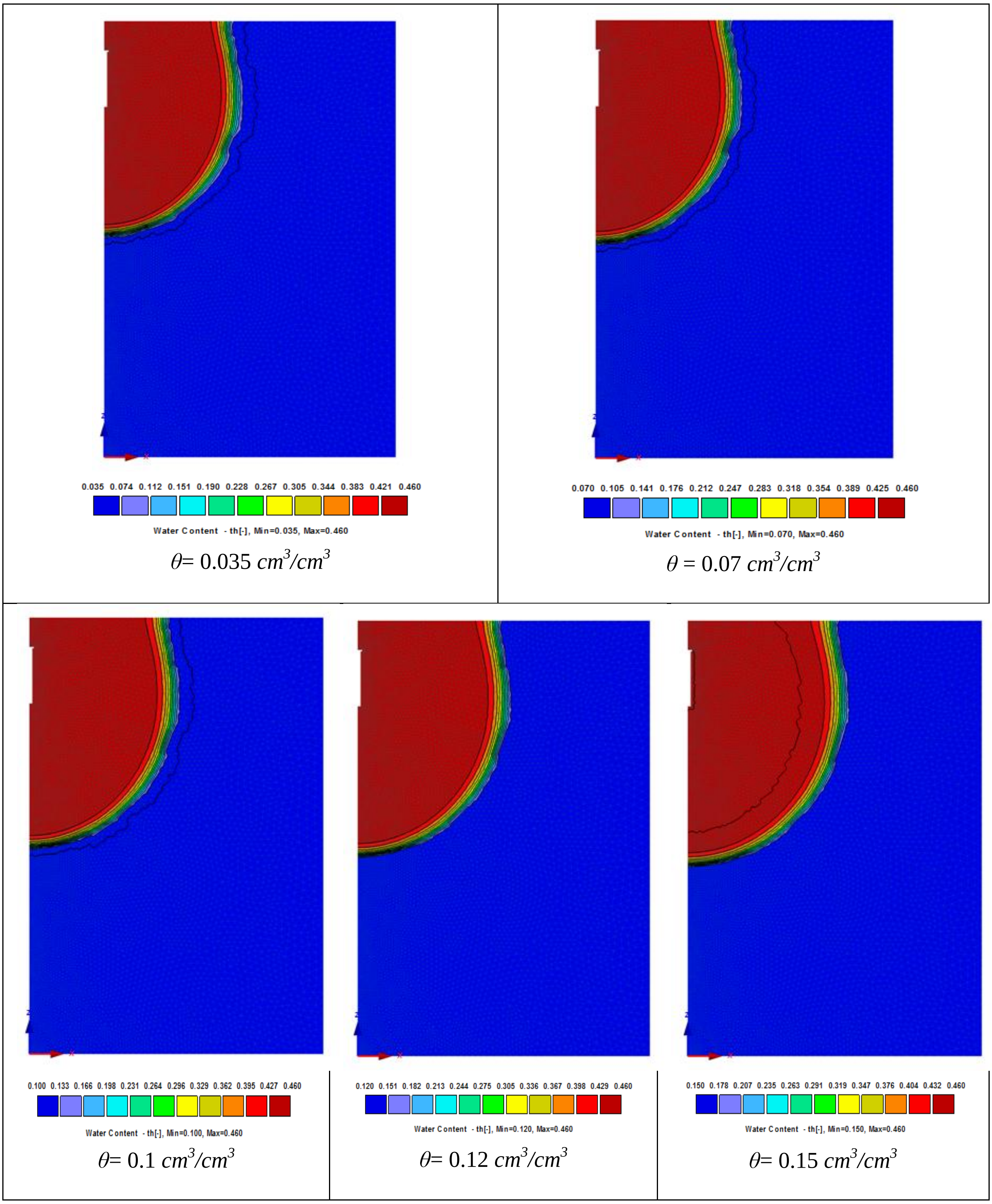


Figure 4. Simulation of wetting patterns from a ceramic pipe in silt soil with 1.0 x1.5 m domain, pipe length= 20 cm, pipe hydraulic conductivity = 0.005 cm/hr, applied head= 200 cm, and with different initial soil water contents after 36 hr.

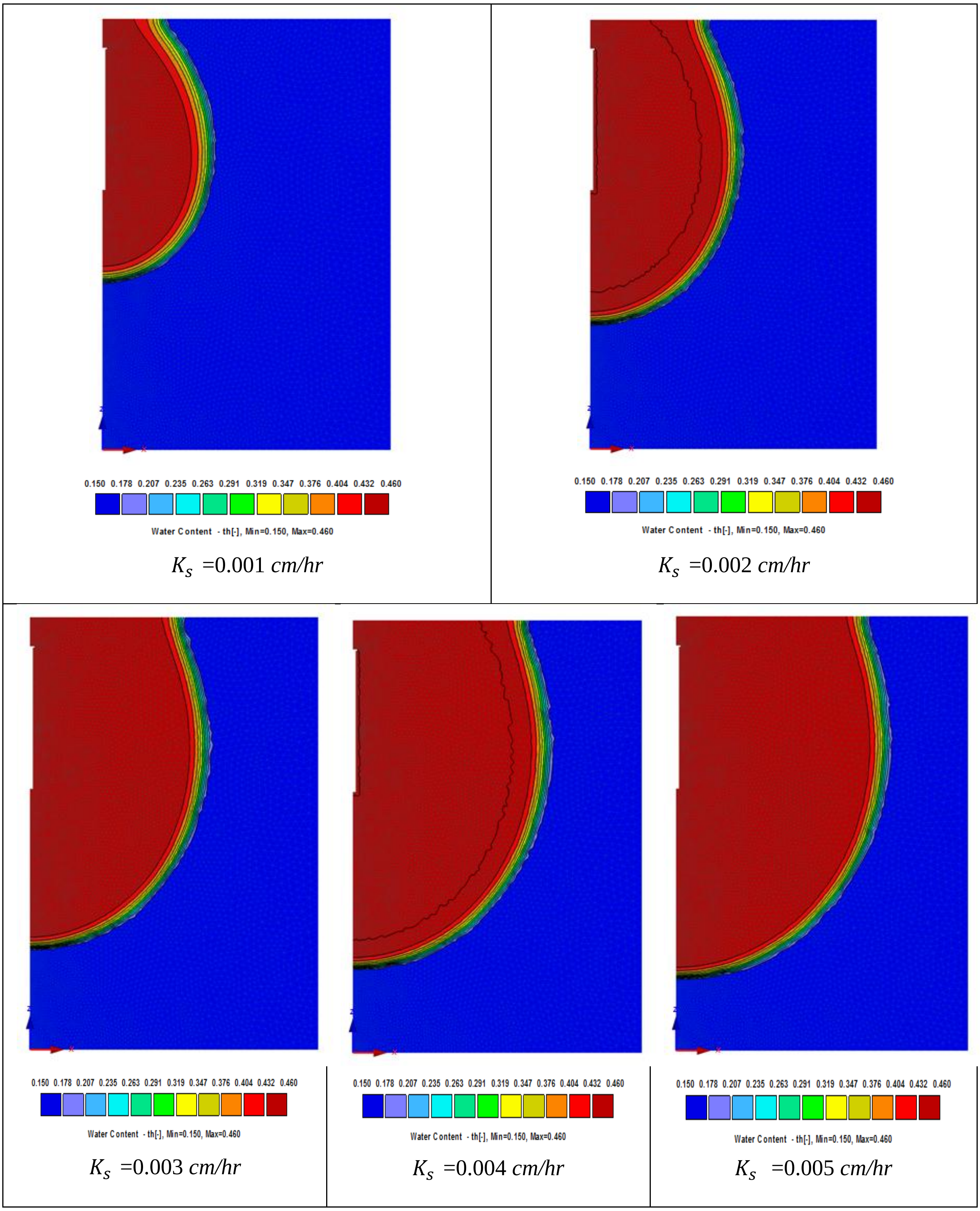


Figure 5. Simulation of wetting patterns from a ceramic pipe in silt soil with 1.0 x1.5 m domain, pipe length =50 cm, initial soil water content= 0.15 cm^3/cm^3, applied head =200 cm, and with different pipe hydraulic conductivities after 36 hr.

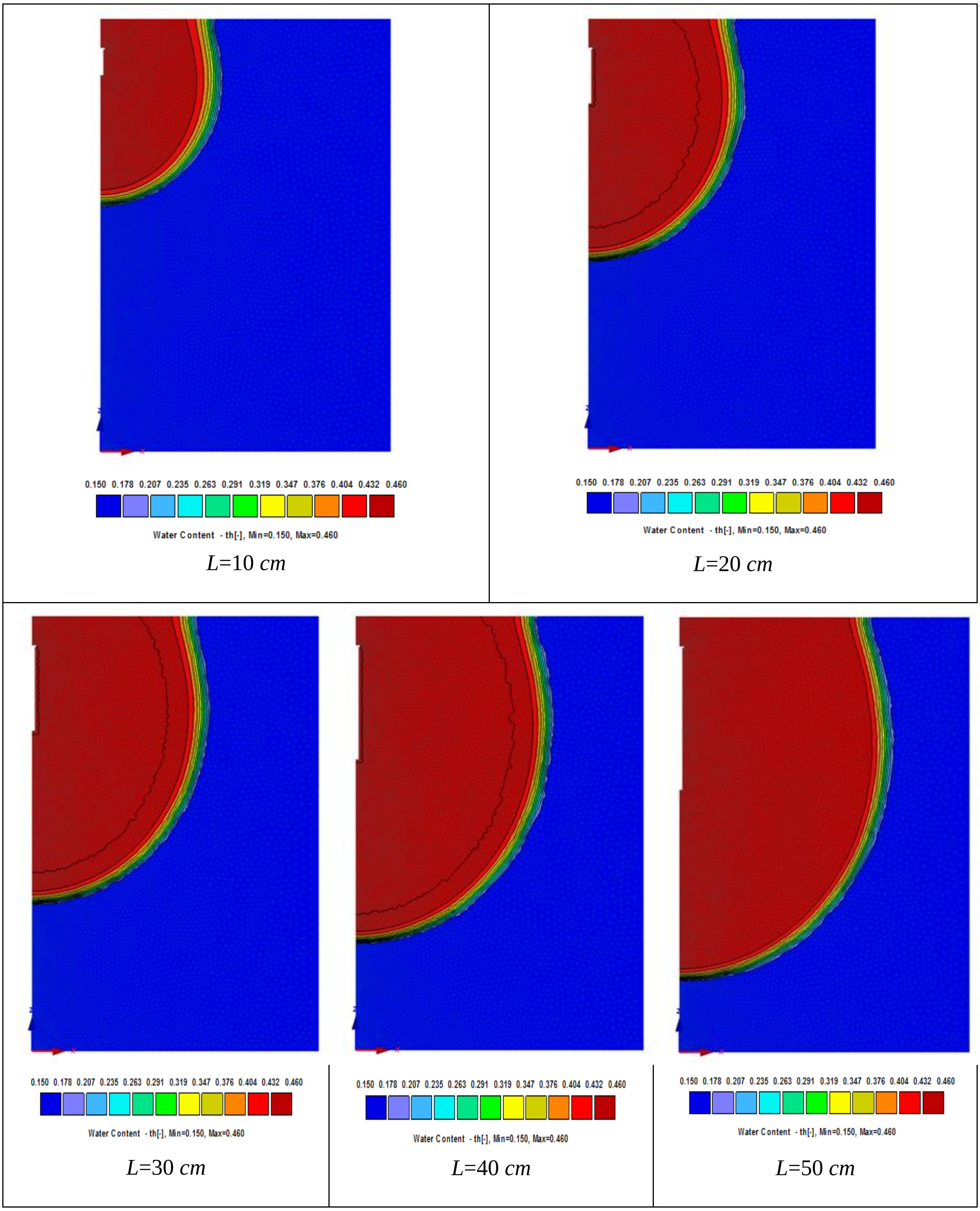


Figure 6. Simulation of wetting patterns from a ceramic pipe in silt soil with 1.0 x1.5 m domain, initial soil water content= 0.15cm^3/cm^3, pipe hydraulic conductivity=0.005 cm/hr, applied head=200 cm, and with different pipe lengths after 36 hr.

Table 1. Values of initial soil water content used for the simulations in USDA classification system.

Soil texture	Initial volumetric soil water content, θ, cm^3/cm^3				
Silty Loam	0.090	0.110	0.130	0.150	0.170
Clay Loam	0.100	0.115	0.130	0.145	0.160
Silt	0.035	0.070	0.100	0.120	0.150
Clay	0.130	0.135	0.140	0.145	0.150
Silty Clay Loam	0.100	0.115	0.130	0.145	0.160

Table 2. Values of applied hydraulic heads at the soil surface.

Soil texture	Applied head, h, cm				
Silty Loam	50	75	100	150	200
Clay Loam	100	125	150	175	200
Silt	25	50	100	150	200
Clay	100	125	150	175	200
Silty Clay Loam	100	125	150	175	200

Table 3. Values of hydraulic conductivity of the buried ceramic pipe.

Soil texture	Pipe hydraulic conductivity, K_s , cm/hr				
Silty Loam	0.0010	0.0020	0.0030	0.0040	0.0050
Clay Loam	0.0005	0.0006	0.0007	0.0008	0.0009
Silt	0.0010	0.0020	0.0030	0.0040	0.0050
Clay	0.000100	0.000105	0.000110	0.000115	0.000120
Silty Clay Loam	0.0002	0.0003	0.0004	0.0005	0.0006

Table 4. Empirical formulas to predict wetted width for different soils.

Soil texture	Wetted width, X , cm
Silty Loam	$6.752\ t^{0.539}\ K_s^{0.420}\ L^{0.335}\ h^{0.352}\ \theta^{0.199}$
Clay Loam	$16.349\ t^{0.543}\ K_s^{0.459}\ L^{0.146}\ h^{0.349}\ \theta^{0.233}$
Silt	$5.439\ t^{0.521}\ K_s^{0.394}\ L^{0.337}\ h^{0.315}\ \theta^{0.098}$
Clay	$4.973\ t^{0.430}\ K_s^{0.182}\ L^{0.088}\ h^{0.185}\ \theta^{0.183}$
Silty Clay Loam	$13.710\ t^{0.432}\ K_s^{0.369}\ L^{0.086}\ h^{0.281}\ \theta^{0.158}$

Table 5. Empirical formulas to predict wetted depth for different soils.

Soil texture	Wetted depth, *Z*, *cm*
Silty Loam	$9.977\ t^{0.183}\ K_s^{0.164}\ L^{0.558}\ h^{0.134}\ \theta^{0.096}$
Clay Loam	$6.325\ t^{0.048}\ K_s^{0.051}\ L^{0.637}\ h^{0.035}\ \theta^{0.028}$
Silt	$9.579\ t^{0.186}\ K_s^{0.154}\ L^{0.542}\ h^{0.113}\ \theta^{0.047}$
Clay	$3.469\ t^{0.032}\ K_s^{-0.028}\ L^{0.639}\ h^{0.013}\ \theta^{-0.0005}$
Silty Clay Loam	$5.204\ t^{0.026}\ K_s^{0.023}\ L^{0.657}\ h^{0.014}\ \theta^{0.009}$

Table 6. Statistical analysis of the comparison between wetting patterns width obtained by using HYDRUS/2D and those predicted by the empirical formulas.

Soil texture	RMSE, *cm*	R^2	MAPE %
Silty loam	0.99	0.992	5.41
Clay loam	0.40	0.987	4.81
Silt	1.21	0.989	5.41
Clay	0.30	0.979	3.66
Silty clay loam	0.41	0.962	6.30

Table 7. Statistical analysis of the comparison between wetting patterns depth obtained by using HYDRUS/2D and those predicted by the empirical formulas.

Textural class	RMSE, *cm*	R^2	MAPE %
Silty loam	3.68	0.965	5.05
Clay loam	1.43	0.990	3.18
Silt	3.54	0.967	4.74
Clay	1.25	0.992	3.01
Silty clay loam	1.20	0.992	3.02