



# Modelling of water infiltration and soil swelling in a vertisol from Guadeloupe

Stephane Ruy, Yves-Marie Cabidoche, Liliana Di Pietro

## ► To cite this version:

Stephane Ruy, Yves-Marie Cabidoche, Liliana Di Pietro. Modelling of water infiltration and soil swelling in a vertisol from Guadeloupe. *Geophysical Research Abstracts*, 1999, 1 (2), pp.322. hal-02695591

**HAL Id: hal-02695591**

**<https://hal.inrae.fr/hal-02695591>**

Submitted on 1 Jun 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1

1

2

3

4

5 **Modelling of water infiltration and soil swelling in a vertisol from Guadeloupe**

6

7 S. Ruy<sup>1,\*</sup>, Y.M. Cabidoche<sup>2</sup> and L. Di Pietro<sup>3</sup>

8 <sup>1</sup> and <sup>3</sup>: INRA - Science du Sol; Domaine St Paul; Agroparc; 84914 Avignon Cedex 9;

9 FRANCE. <sup>2</sup>: INRA - AgroPédoClimatologie; Domaine Duclos; Prise d'Eau; 97140 Petit-

10 Bourg; French West Indies.

11 Email: <sup>1</sup> [ruy@avignon.inra.fr](mailto:ruy@avignon.inra.fr); <sup>2</sup>: [cabidoch@antilles.inra.fr](mailto:cabidoch@antilles.inra.fr); <sup>3</sup>: [lili@avignon.inra.fr](mailto:lili@avignon.inra.fr)

12 \*: corresponding author.

13

14

15 **MS-No: HSA6.4-0007**

16

## 1Abstract

2Models of water infiltration in undisturbed swelling soils rely on a dual porosity concept:  
 3Darcy flow in the micro (matric) porosity and by-pass flow in cracks. In vertisols a third  
 4component must be added: the structural porosity, excluding cracks, formed by the soil  
 5microfauna activity and containing water easily available for plants. A model was  
 6implemented to study the mechanisms of water infiltration: (i) water infiltration in the matric  
 7porosity is modelled by the Darcy's law, (ii) the flow in the structural porosity is a gravity-  
 8dominated flow, (iii) water entering cracks is instantaneously added at the bottom of the  
 9cracks. Water movements from structural to matric porosity and from crack's wall into soil  
 10matrix are accounted for. Cracks' opening is a function of soil matrix moisture. Shrinkage  
 11curve, retention curve and hydraulic conductivity of the matrix were measured in the  
 12laboratory. The anisotropy ratio of soil deformation was measured *in situ*. Experiments were  
 13conducted *in situ* to fit some soil structure parameters and test the model. Although not  
 14wholly validated because of a poor modelling of infiltration in structural porosity, the model  
 15already shows that infiltration in this soil is a 3D process and that water infiltration in  
 16structural porosity is the main factor of rainfall partition between vertical infiltration in the  
 17soil matrix and water flow into the cracks.

## 181- Introduction

19A model of infiltration and soil deformation in a Vertisol should account for three porosity  
 20compartments (Cabidoche & Ozier-Lafontaine, 1995; Ruy, 1997): macro-cracks delimiting  
 21continuous soil prisms, intra-prism structural porosity and matric porosity. The almost vertical  
 22macro-cracks, several centimetres wide and several decimetres apart, open and close as the  
 23clay particles reorganise in response to soil moisture changes. Water entering these cracks  
 24may infiltrate laterally into the walls of the soil matrix. The matric porosity is formed by the  
 25arrangement of clay particles. Matric pores are less than 5  $\mu\text{m}$  in width. They remain saturated

1during structural and normal shrinkage and thus contain the water responsible for soil  
2movement. The limit between structural and normal shrinkage is called the crack air entry  
3(CAE) point. The intra-prism structural porosity has a relatively stable geometry (Cabidoche  
4& Ozier-Lafontaine, 1995). Structural pores are from 10 µm to several mm in width (Ruy,  
51997). Structural water does not induce any deformation of the soil. Shrinkage cracks are not  
6included in structural porosity.

7In order to better understanding the processes of water infiltration in an undisturbed swelling  
8clay soil, we present the physical bases of a 2D numerical model of water infiltration and soil  
9movements in a Vertisol.

## 102- Physical bases and description of the model

11The model is 2D, the scale of modelling is a half prism isolated by one macro-crack. The  
12experimental size of a prism can be deduced from the network of macro-cracks and is about  
1370 cm.

### 14(i) water flow in the matric porosity

15We assume that water flow is described by Darcy's law because of the small diameter and the  
16homogeneous distribution of the size of the matric pores (Ruy, 1997). 2D Richard's equation  
17is used to calculate water fluxes. A source function  $S_w$  accounts for the diffusive water  
18movement from structural porosity to matric porosity, as suggested by Jarvis (1994):

$$S_w = K_{w/s}(\psi_{mat}) \cdot S_{struc} \cdot \frac{\psi_{struc} - \psi_{mat}}{d^2}, \quad (1)$$

19where  $K_{w/s}$  (cm s<sup>-1</sup>) is the matric conductivity,  $\psi_{mat}$  (cm) the potential of water in matric  
20porosity,  $\psi_{struc}$  (cm) the potential of water in structural porosity,  $S_{struc}$  the saturation of  
21structural porosity and  $d$  (cm) an effective "diffusion" length. We suppose that the potential of  
22water in the structural porosity is a linear function of the saturation of this porosity:  $\psi_{struc}$  is  
23equal to 0 cm when the structural porosity is saturated and is equal to  $\psi_{ae}$  when it is air filled,  
24where  $\psi_{ae}$  is the soil water potential at the CAE point (Ruy, 1997). The water retention curve,

the shrinkage curve and the matric hydraulic conductivity were measured according to the methods described in Ruy & Cabidoche (1998).

We used the finite element method to discretize the domain with rectangular elements. The boundary condition at the surface is a Neumann's condition according to (iv). A zero flux condition is imposed at the bottom of the profile and along the vertical axis of the soil prism, because of the symmetry of the soil prism. The boundary condition along the macro-crack wall is a function of the depth of ponded water in the crack and is described in subsection (iii).

#### (ii) water flow in the intra-prism structural porosity

Previous work (Ruy, 1997) showed that water flow inside the prism could not be modelled by Darcy's law with a bimodal hydraulic conductivity and water retention curve, and therefore that water flow inside the structural porosity was of "preferential flow type". Then, we assume that water flow in the structural porosity is a gravity flow. Water flow is described in a conceptual way by using a model of reservoirs in cascade (one reservoir per layer). For each layer, the volume of the reservoir is the volume of the structural porosity. The output flux  $q$  of each reservoir (Figure 1) is a power function of the saturation of the reservoir:

$$q = c \cdot S_{\text{struc}}^b, \quad (2)$$

where  $c$  ( $\text{cm s}^{-1}$ ) is the unknown hydraulic conductance,  $S_{\text{struc}}$  the saturation of the reservoir (i.e. the saturation of the structural porosity) and  $b$  an empirical exponent. Theoretical values of  $b$  can be calculated from the laminar film flow theory in a single, smooth and vertical macropore. For open channel flow, a power law function similar to eq. (2) relates the flow and the depth of water. The value of the exponent depends on the Reynold's number (Chen & Wagenet, 1992). The flow is assumed to be turbulent, and we set the value of  $b$  to 1.5.

#### (iii) water flow into the macro-cracks

In the model, water infiltrating into the macro-crack instantaneously reaches the bottom of the crack where it accumulates. Horizontal infiltration into the soil prism during downward unsaturated flow along the macro-crack wall is neglected, whereas it is taken into account for

1 ponded conditions at the bottom of the macro-crack. Hence, the lateral boundary condition for  
 2 the resolution of the 2D Richard's equation is a zero flux condition above the surface of the  
 3 ponded water, and a Dirichlet's condition below this surface (hydrostatic profile). At each  
 4 time step, the model recalculates the volume of the macro-crack and the depth of the surface  
 5 of the ponded water according to a mass balance and to the deformation of the soil matrix.

#### 6 *(iv) partitioning of rainfall at the soil surface*

7 Rainfall,  $R$ , is partitioned at the soil surface according to the infiltrability of the three  
 8 porosities: first,  $R$  enters the matric porosity, then excess water flows into the structural  
 9 porosity and then into the macro-cracks. The model calculates infiltrability of the three  
 10 porosities.

#### 11 *(v) deformation of the soil matrix*

12 Clay particles reorganise as water infiltrates into matric porosity, and the soil prism is  
 13 deformed in every direction according to the anisotropy ratio of soil movements. Swelling is  
 14 supposed to be normal. We used in the model the anisotropy ratio  $k$  of Voltz & Cabidoche  
 15 (1995):  $k$  is the elongation rate in any horizontal direction divided by the elongation rate in the  
 16 vertical direction. The model deforms each finite element at each time step according to the  
 17 variation of the mean matric WC of the element.

18 Table 1 presents a synthesis of all the equations used in the model.

## 19 **3- Material and methods**

### 20 **3.1- Description of the experiments**

21 The model was tested on a Vertisol at the Experimental Research Station of INRA in Gardel,  
 22 Guadeloupe (French Antilles). The soil is a chromic vertisol, with more than 80 % clay.

23 Several soil prisms were isolated from the plot by a polyethylene sheet coated with a hull of  
 24 resin and fibreglass. A side of the hull was replaced by a rigid inox steel-plate on which the  
 25 measurement devices were fixed. Four windows were cut into the inox sheet and equipped

1with Plexiglas plates. Potentiometric sensors were fitted on the remaining Plexiglas windows  
 2to measure the horizontal deformation of a soil prism at different depths. All the displacement  
 3sensors were installed on the same soil prism. Thickness variations of prism layers were  
 4measured with modified THERESA<sup>®</sup> transducers (Cabidoche & Ozier-Lafontaine, 1995).  
 5Transducers were fitted with the same potentiometric displacement sensors. Water was  
 6applied at the soil surface with four full cone nozzles or with a portable sprayer for low  
 7intensities.

8The matric WC was calculated with the model of Voltz & Cabidoche (1995) from thickness  
 9variations of prism layers. The structural WC was not measured. A piezometer was fitted into  
 10a macro-crack: an ultrasonic probe automatically measured the level of ponded water.

### 113.2- Fitting of unknowns parameters

12Structural conductance  $c$  and diffusion length  $d$  must be fitted from experimental data. Both  
 13parameters are soil structure parameters: they should vary with depth because the volume and  
 14the shape of the structural pores vary with depth. We considered two different values for  $c$ :  
 15 $c_{\text{surf}}$  (layers 0-10 cm and 10-30 cm) and  $c_{\text{deep}}$  (30-50 cm to 90-110 cm).  $c$  is nil at 130 cm,  
 16because of the impervious layer. Three different values were considered for  $d$ :  $d_{\text{surf}}$  (0-10 cm,  
 1710-30 cm, 30-50 cm),  $d_{\text{mid}}$  (50-70 cm, 70-90 cm) and  $d_{\text{deep}}$  (90-110 cm and 110-130 cm).  
 18Therefore 5 parameters must be fitted from experiments. We used the Marquardt's method  
 19(1963). Six experiments were conducted. The first (Exp1 to Exp5) five were used to calibrate  
 20the model, the last one (Exp6) was used to "validate" the model.

## 214- Results and Discussion

### 224.1- Submodels validation

23The model has been checked against experimental data obtained in a 1D swelling bentonite  
 24paste (Angulo, 1989; Figure 1). Then, we used the model in two domains (matric porosity and  
 25macro-cracks). A rainfall of 120 mm h<sup>-1</sup> for 6 min was simulated (frequency 0.9 year<sup>-1</sup> in the

1Grande-Terre Island of Guadeloupe). Figure 2 shows that most of the rain flows into the  
 2macro-crack where it accumulates and then infiltrates into the soil prism, resulting in both  
 3horizontal and vertical swelling of the prism. The pattern of the heterogeneity of water  
 4potentials inside the prism is very similar to the spatial variability of the water content  
 5measured in the field (Jaillard & Cabidoche, 1984). Therefore, we consider that these  
 6quantitative and qualitative results validate the model when run with 1 or 2 domains.

#### 74.2- Experiments results

8Macro-crack flow has never been observed, except in the last experiment. For each  
 9experiment, the variation in the swelling measured by transducers is quite large, which is due  
 10to a high spatial variability of the structural porosity. During the last experiment, the swelling  
 11velocity of a given soil layer increases as the level of water into the macro-crack reaches this  
 12layer. It shows that lateral infiltration into the prism of water running rapidly downwards  
 13along cracks has to be neglected and that it must be taken into account under the level of  
 14ponded water into the macro-crack. Figure 3 shows the relation between the horizontal  
 15elongation rate and the vertical one: the slope of the regression line is the anisotropy ratio  $k$ .  
 16The mean value of  $k$  is 0.798 in layer 10-30 cm depth and is 1.152 in layer 30-50 cm depth. It  
 17is in agreement with the value of 0.85 calculated by Cabidoche & Voltz (1995). We used a  
 18single value of 0.826 for all layers in the model.

#### 194.3- Calibration

20For each experiment, the uniqueness of the parameters has been verified (Ruy, 1997).  
 21Measured and simulated swelling of 30-50 cm depth soil layer during Exp3 is plotted on  
 22Figure 4. For each experiment, a unique set of parameters can be fitted to well simulate the  
 23vertical swelling of all soil layers. However, the fitted parameters differ significantly from one  
 24experiment to the other: for instance the fitted value (with the 95 % CI) of  $d_{\text{surf}}$  was 0.28 cm  
 25( $\pm 0.01$ ) for Exp2, 0.52 cm ( $\pm 0.03$ ) for Exp3, 0.29 cm ( $\pm 0.04$ ) for Exp4 and 0.44 cm ( $\pm$



10.01) for Exp5. As the size of aggregates is a function of the matric WC, we tried to relate  $d_{\text{surf}}$  to the initial matric WC of the 10-30 cm layer, but the regression was not significant. Fitted values of  $c_{\text{surf}}$  and  $c_{\text{deep}}$  also differ from one experiment to another. They can be explained neither by the initial matric WC, nor by rainfall intensity  $R$ .

#### 54.4- Validation

6Finally, we tested the model with the independent data set collected during Exp6. Parameter values used in the simulation are the mean value that were fitted for Exp1 to Exp5: 0.440 cm for  $d_{\text{surf}}$ , 2.45 cm for  $d_{\text{mid}}$ , 2.62 cm for  $d_{\text{deep}}$ , 0.0434 cm s<sup>-1</sup> for  $c_{\text{surf}}$  and 0.0478 cm s<sup>-1</sup> for  $c_{\text{deep}}$ . Values of  $c_{\text{surf}}$  and  $c_{\text{deep}}$  are those fitted in Exp5 because rainfall intensities of Exp5 and Exp6 are close. Results are presented in Figures 5a and 5b. Neither the range of swelling nor its rate are simulated in a satisfactory way. The beginning of water infiltration into the macro-crack is delayed by the model, because of the high infiltrability of the structural porosity (structural conductance of 0.0434 cm s<sup>-1</sup> at the surface). However, the upraising of the water level is well simulated. After rainfall has stopped, the decrease of the water level in the macro-crack is not well simulated. However, at least two reasons can explain this discrepancy. (i) clogging of the piezometer by deposit of clay particles: therefore, the level recorded inside the piezometer is higher than the water level in the macro-crack; (ii) artefacts of simulation: as the macro-crack closes up, a small variation in the amount of water in the macro-crack results in a large variation in the level of water.

#### 205. Discussion and conclusion

21Germann & Di Pietro (1996) distinguished two kinds of flow in macropores, *i.e.* dispersive and preferential flow. They showed (see Table 3 of Germann & Di Pietro, 1996) that conductance is constant when water infiltration is governed by preferential flow (for large input rates of water), and increases with the rainfall intensity when the flow in macropores is dispersive (for low input rates). In our experiments, low input rates of water in Exp2, Exp3

1 and at the beginning of Exp4 could be responsible for a dispersive infiltration, whereas the  
 2 second part of Exp4 and Exp5 could have been governed by preferential flow. However, this  
 3 result cannot explain the difference between Exp2 and Exp3 where rainfall intensities are the  
 4 same. In fact, other factors, such as geometry and initial saturation of structural porosity, have  
 5 an influence upon the value of structural conductance. These authors also showed that  
 6 gravity-dominated flow could be either of the preferential type or of the dispersive type: in  
 7 their experiments, the value of  $b$  was not constant but may be used to assess the degree of  
 8 preferential flow.  $b$  decreased with increasing application rates of water. Its value was about 4  
 9 for a preferential flow (application rate of water equal to about  $360 \text{ mm h}^{-1}$ ), and increased up  
 10 to 8 for a more dispersive flow (application rate of about  $36 \text{ mm h}^{-1}$ ). New calibration could  
 11 be conducted with  $b$  as an unknown parameter. However, the total number of parameters  
 12 would increase and parameter  $b$  and  $c$  would probably not be independent.

13 Hypothesis that structural flow is of preferential type came from the results of Ruy (1997).  
 14 However, the experimental uncertainty in the calculation of structural and matric WC was  
 15 quite important. It is possible that Darcy's law may apply on one part of the structural flow (in  
 16 the smallest pores) and that a gravity-dominated flow may be used for the other part of the  
 17 structural flow, as the range of variation of the pore diameters is quite large. We used the  
 18 Wind's evaporation method (Tamari *et al.*, 1993) to obtain the hydraulic conductivity of the  
 19 structural porosity ("structural conductivity") on one saturated clod sampled in the 70-80 cm  
 20 layer. Results are only approached as the shrinkage is not accounted for in this method, but  
 21 we see (Figure 6) a good agreement between the matric conductivity and the structural  
 22 conductivity, showing that Darcy's law could be used at least in one part of the structural  
 23 porosity.

24 Nevertheless, the model already shows that water infiltration in a Vertisol is a 3D process and  
 25 that the structural water flow is the main factor of the partition of rainfall between vertical

infiltration in the prism and water flow in macro-cracks, as can be showed in Figures 7a and 27b.

### 3Acknowledgements

4We are grateful to MM. J. André, T. Bajazet and A. Mulciba for their technical assistance  
5during the experiments.

### 6References

- 7Angulo-Jaramillo, R., Caractérisation hydrodynamique de sols déformables partiellement  
8saturés. Etude expérimentale à l'aide de la spectrométrie gamma double-sources, PhD. Thesis,  
9Université de Grenoble-INPG, 1989.
- 10Cabidoche, Y.M. and Ozier-Lafontaine, H., THERESA I Matric water content measurements  
11through thickness variations in vertisols. *Agricultural Water Management*, 28, 133-147, 1995.
- 12Cabidoche, Y.M. and Voltz, M., Non-uniform volume and water content changes in swelling  
13clay soil: II. A field study on a Vertisol. *European Journal of Soil Science*, 46, 345-355, 1995.
- 14Chen, C. and Wagenet, R.J., Simulation of water and chemicals in macropore soils. Part 1  
15Representation of the equivalent macropore influence and its effect on soil water flow.  
16*Journal of Hydrology*, 130, 105-126, 1992.
- 17Germann, P.F. and Di Pietro, L., When is porous media flow preferential? A hydromechanical  
18perspective. *Geoderma*, 74, 1-21, 1996.
- 19Jaillard, B. and Cabidoche, Y.M., Etude de la dynamique de l'eau dans un sol argileux  
20gonflant: dynamique hydrique. *Science du sol*, 22, 239-251, 1984.
- 21Jarvis, N.J., The MACRO model (version 3.1): technical description and samples simulations.  
22Reports and Dissertations 19, Swedish University of Agricultural Sciences (Uppsala), 1994.
- 23Ruy, S., Les trois voies simultanées de l'infiltration dans un vertisol de la Guadeloupe: étude  
24expérimentale et numérique. PhD Thesis, University of Montpellier, 1997.
- 25Ruy, S. and Cabidoche, Y.M., Hydraulic conductivity of the matric porosity of an unsaturated  
26Vertisol: a field and laboratory comparison. *European Journal of Soil Science*, 49, 175-185,  
271998.
- 28Voltz, M. and Cabidoche, Y.M., Non-uniform volume and water content changes in swelling  
29clay soil: I. Theoretical analysis. *European Journal of Soil Science*, 46, 333-343, 1995.
- 30Tamari, S., Bruckler, L., Halbertsma, J. and Chadoeuf, J., A simple method for determining  
31soil hydraulic properties in the laboratory. *Soil Science Society of America Journal*, 57, 642-  
32651, 1993.

## 1Tables and Figures caption

### 2Tables

3Table 1: equations used in the model to described water flow inside and between the three  
4kinds of porosity.

### 5Figures

6Figure 1: comparison between the model and experimental data from Angulo (1989) for the  
7profiles of water content during an infiltration in a 1D-swelling bentonite paste.

8Figure 2: simulation of water potential distribution inside a prism of a Vertisol during and  
9after rainfall.

10Figure 3: relation between the horizontal elongation rate and the vertical one. Only continuous  
11drying periods have been considered, a different number and symbol label each period. The  
12slope of each regression line is the anisotropy ratio  $k$ . Average values of  $k$  are calculated from  
13a weighted mean, the weight being inversely proportional to the estimation variance of  $k$ .

14Figure 4: variation of the measured and simulated swelling of the 30-50 cm depth layer during  
15Exp3. Continuous lines are for the 60 % confidence interval.

16Figure 5: simulation of Exp6 with parameters fitted from Exp1 to Exp5. (5a): variation of the  
17measured and simulated swelling of the 10-30 cm depth layer; continuous lines are for the 60  
18% CI. (5b): variation of the measured and simulated water level in macro-cracks.

19Figure 6: hydraulic conductivity  $K_{w/s}$  of the matric porosity and of the structural porosity of  
20the 70-80 cm depth layer.  $\theta$  is the volumetric water content ( $\text{m}^3 \text{m}^{-3}$ ).

21Figure 7: simulation of: (7a) the cumulated water flow in the three porosities during and after  
22rainfall ( $I=71 \text{ mm h}^{-1}$  for 54 min); and (7b) the cumulated flow in the matric porosity from the  
23soil surface, from the macro-crack and from structural pores

24

1

1  
2

Table 1

porosity	law of motion	Equations mass balance	water exchanges:
matric	Darcy's law : $\mathbf{q}_{\text{mat}} = -K_{w/s}(\psi) \cdot \nabla(\psi + z)$ 2D	Richards' equation: $C(\psi) \cdot \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x} \left( K_{w/s}(\psi) \cdot \frac{\partial \psi}{\partial x} \right) + \frac{\partial}{\partial z} \left( K_{w/s}(\psi) \cdot \left( \frac{\partial \psi}{\partial z} + 1 \right) \right) + S_w$	$S_w = K_{w/s}(\psi) \cdot S_{\text{struc}} \cdot \frac{\psi_{\text{struc}} - \psi}{d^2},$ $\psi_{\text{struc}} = \psi^{ae} \cdot (1 - S_{\text{struc}})$
structural	Gravity flow across 7 reservoirs: $q_{\text{struc}} = c \cdot S_{\text{struc}}^b, b = 1.5,$ 1D	for the $i$ th reservoir : $\forall i \in [1.7], V_{\text{max},i} \frac{dS_{\text{struc},i}}{dt} = (q_{i-1} - q_i) - \int_i S_w(\theta_{\text{mat}}, S_{\text{struc},i}, z)$	
crack	instantaneously added at the bottom of the macro-crack,	variation of the depth $z^{\text{SL}}$ of the surface of the ponded water according to: <b>(i)</b> the flux of water at the surface of the macro-crack, <b>(ii)</b> the volume of ponded water that infiltrates horizontally into the soil prism, <b>(iii)</b> the swelling of the soil prism,	macro-crack - matric porosity: under the surface of ponded water, Dirichlet boundary condition: $\psi(z \geq z^{\text{SL}}) = z - z^{\text{SL}},$  macro-crack - structural porosity: no exchange
Parameters			
matric porosity	hydraulic conductivity $K_{w/s}(\psi)$ retention curve $\psi(\theta)$ shrinkage curve	measured measured measured	
structural porosity	$c$ $d$ $b$ $\psi^{ae}$	unknown: to fit unknown: to fit 1.5 measured: -316 cm	

3  
4  
5

2

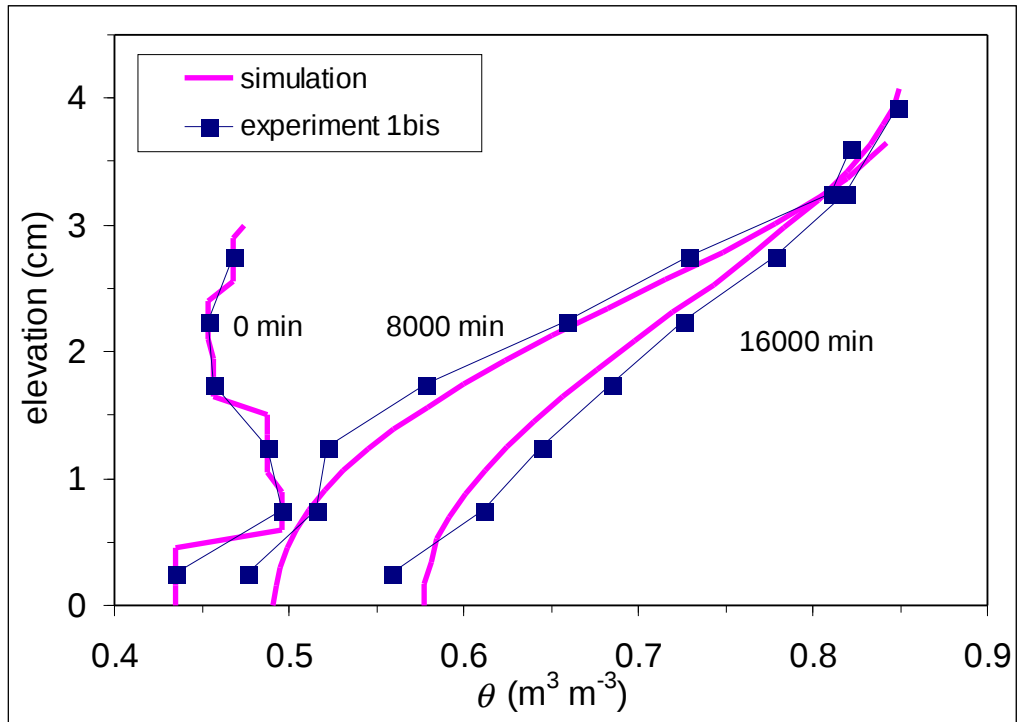
1

1

2

3

Figure 1:



4

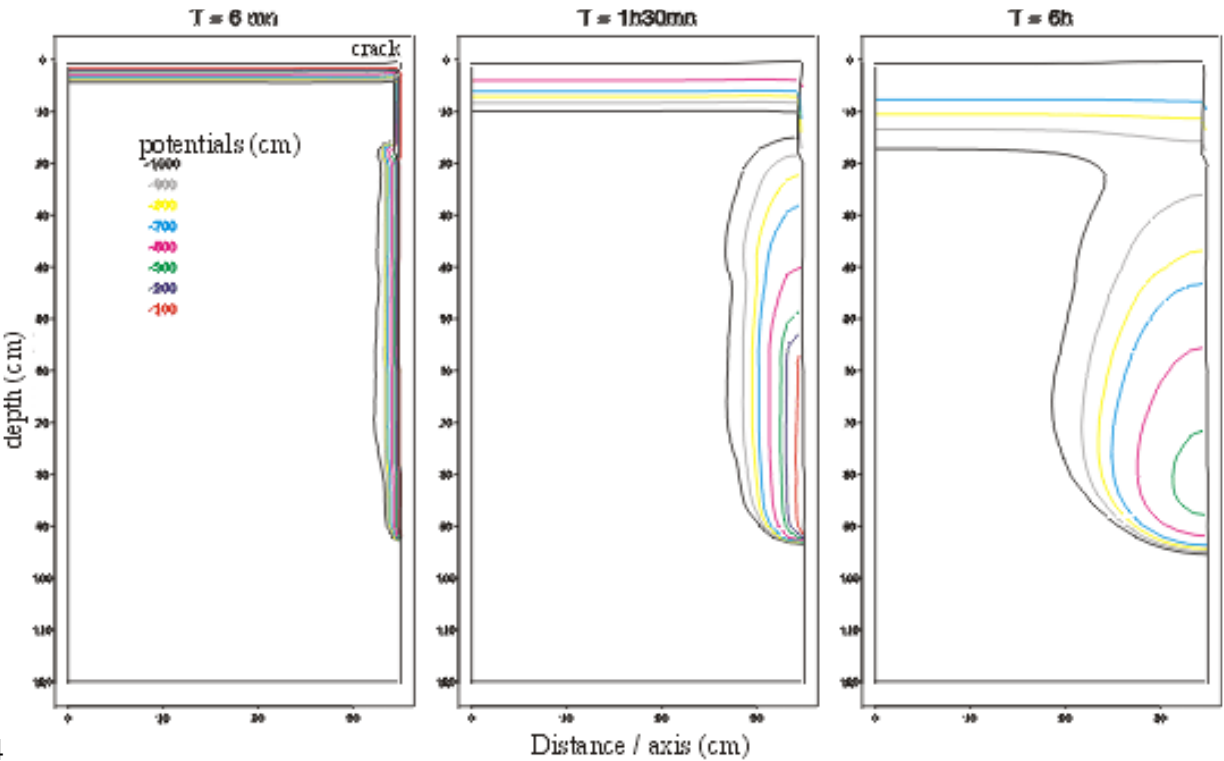
1

1

2

3

Figure 2:



4

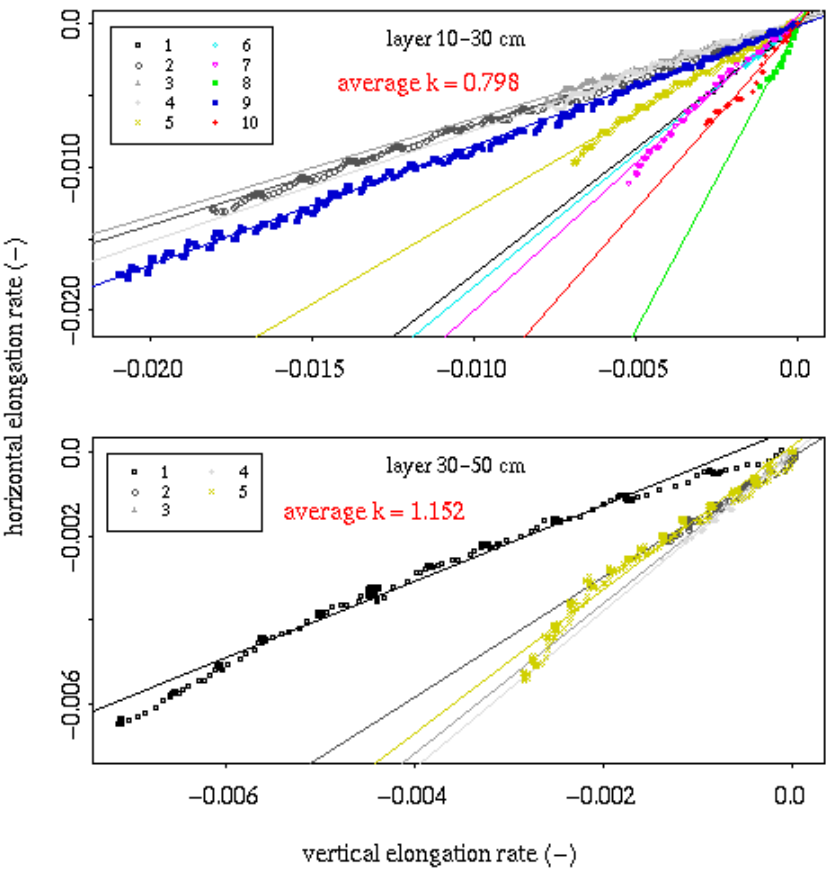
1

1

2

3

Figure 3:



4

5

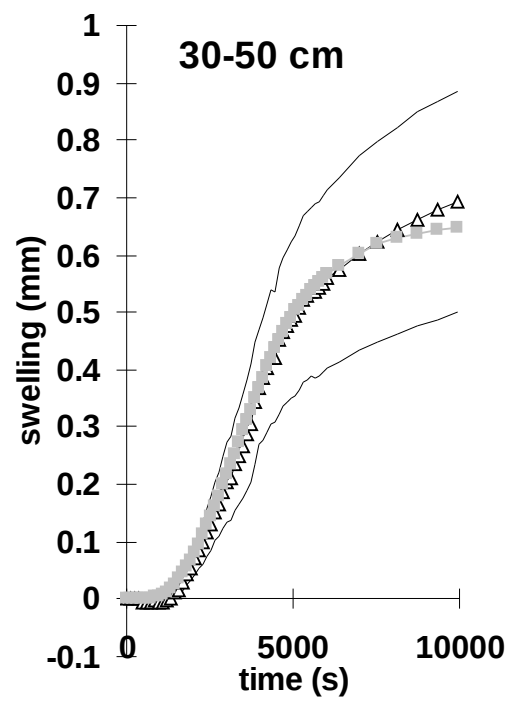


1

1

2

Figure 4

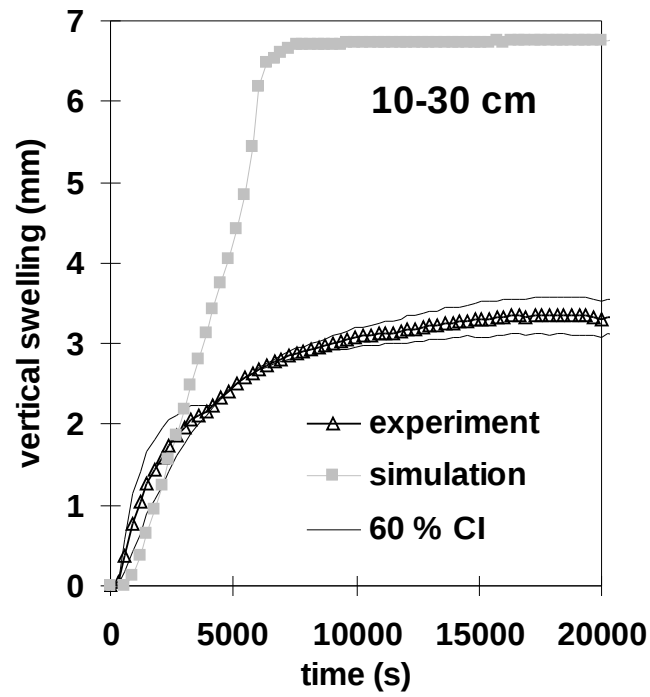


3

1

1

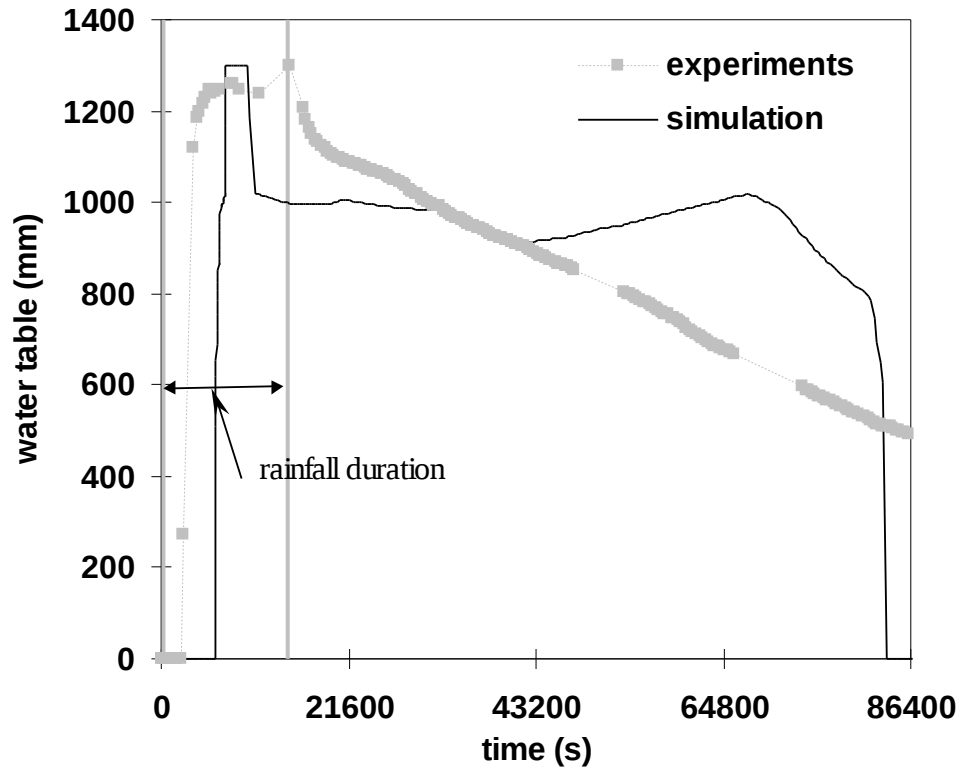
Figure 5:



2

3

Figure 5a



4

5

Figure 5b

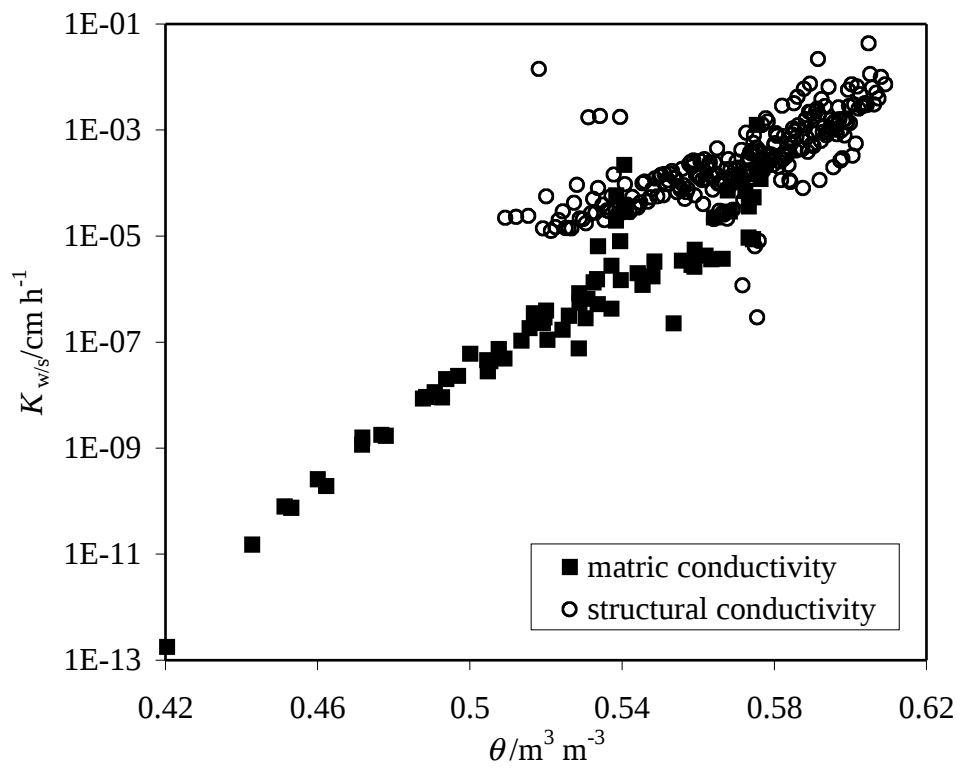
2

1

1

2

Figure 6:



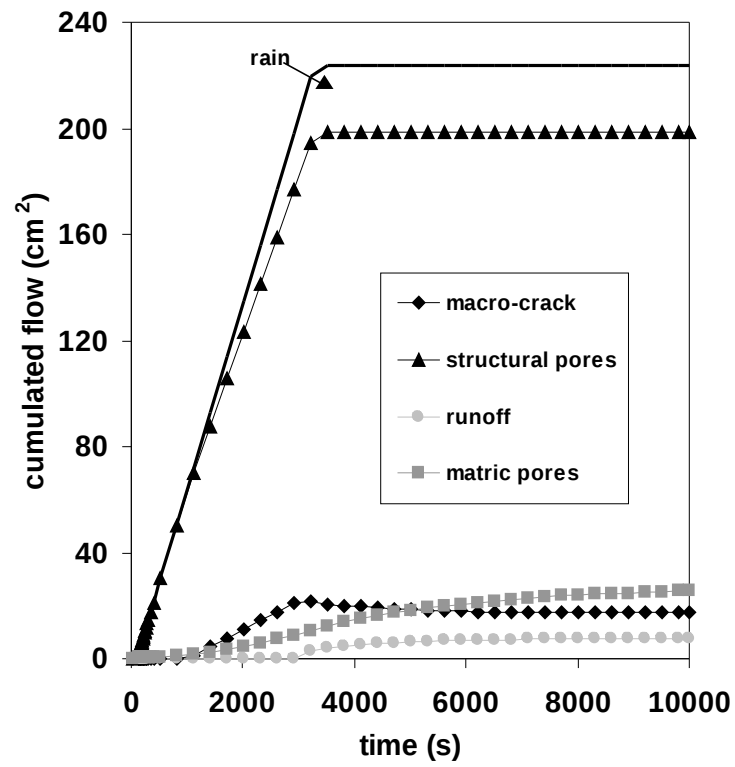
3

4

1

1

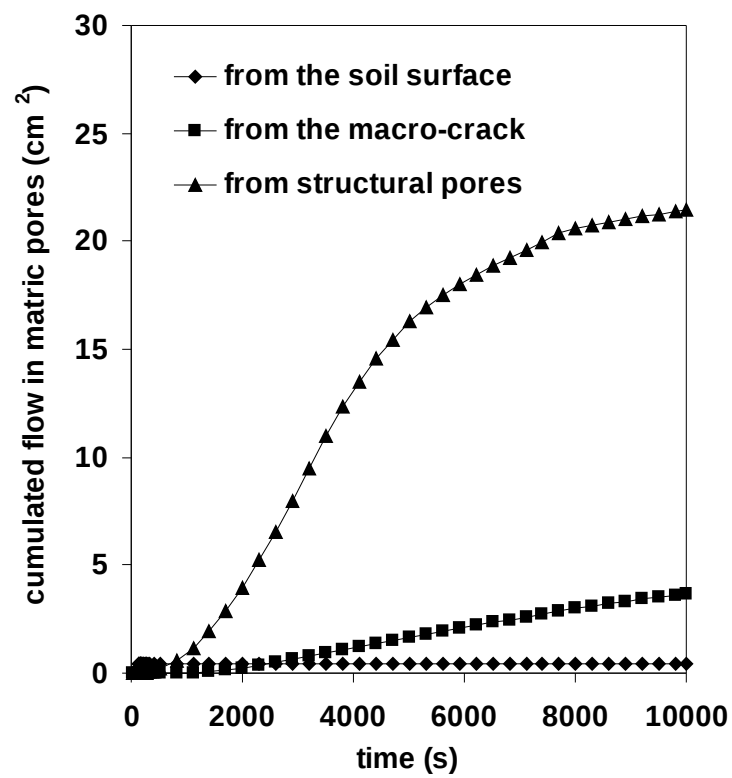
Figure 7:



2

3

Figure 7a



4

5

Figure 7b

2