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A dual-permeability model for simulating water infiltration into unsaturated, fractured and swelling soils

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RIASSUNTO

Un modello a permeabilità duale per la simulazione dei processi di infiltrazione in terreni insaturi, fratturati e rigonfianti.

Il presente lavoro propone un modello a permeabilità duale "evolvente", per l'analisi dei processi di infiltrazione in mezzi porosi rigonfianti e fessurati. Le fessure si comportano come tubi di flusso soggetti a progressivo restringimento per aumento del contenuto d'acqua nella matrice rigonfiante. Parte della portata di afflusso viene trattenuta dalla matrice per infiltrazione verticale mentre parte passa, per effetto della gravità, attraverso le fessure, da cui si infiltra lateralmente nella matrice stessa. Il flusso in matrice è calcolato attraverso l'equazione di Richards in due dimensioni mentre la quantità di acqua che attraversa l'interfaccia è stimata in funzione della disponibilità di acqua in frattura e della massima capacità di assorbimento della matrice.

Il modello considera la presenza, ad una certa profondità, di un livello a maggiore permeabilità che introduce gli effetti indotti dalla stratificazione del terreno dando luogo alla formazione di una barriera capillare.

L'applicazione del modello ad un terreno limoso fessurato ha mostrato come, in caso di precipitazione intensa, il flusso verticale raggiunga in pochi minuti profondità notevoli (1.5 m e più) mentre nel caso di pioggia poco intensa è limitato agli strati più superficiali e avviene in tempi maggiori. Circa il restringimento delle fessure, è emerso un rigonfiamento differenziato e irregolare localizzato in superficie, con chiusura totale delle fratture stesse per piogge deboli e prolungate.

KEY WORDS: *Dual permeability model, fractured swelling soils, preferential flow.*

INTRODUCTION

Infiltration processes in unsaturated heterogeneous or structured soils can be described using dual-porosity or dual-permeability models, which consider two overlapping interacting pore regions (microporous matrix and macropores or fractures). During the last three decades a large number of dual-porosity/permeability models has been developed (ŠIMŮNEK *et alii*, 2003; GERKE, 2006; VAN DAM *et alii*, 2008).

The shrinking-swelling dynamics of clayey soils, which causes the closure of fractures and slows down water flow, is a process that is not widely considered. Only few models (NOVÁK *et alii*, 2002 and few others) try to simulate water flow in unsaturated soils taking into account the swelling process.

Water flow in unsaturated soils can also be significantly affected by capillary barrier phenomena, when a coarse soil underlies a finely textured and fractured surface soil. These phenomena could induce a water storage at the interface between layers and hold water and contaminants delaying transport toward deep groundwater resources. The water storage could also worsen the stability of surface fine deposits, causing a decrease of the shear strength and inducing landslides.

The authors have previously proposed a dual porosity model (GALEANDRO *et alii*, 2012), simulating infiltration in soil into fractured swelling soils and considering progressive narrowing of fractures, as a result of an increase in the water content in the swelling matrix. The model also takes into account the presence of a coarse soil layer underlying the fine fractured soil and the associated capillary barrier effect at the bottom of fractures (MANCARELLA *et alii*, 2012). The applicability of the model is demonstrated on multiple examples, whose results show how the infiltration process can be strongly affected by rainfall intensity, swelling phenomena, and the presence of the capillary barrier, which behavior depends in turn on rainfall intensity.

The model has been now improved considering a dual permeability system with infiltration processes also from the topsoil, that were neglected in the previous dual-porosity model.

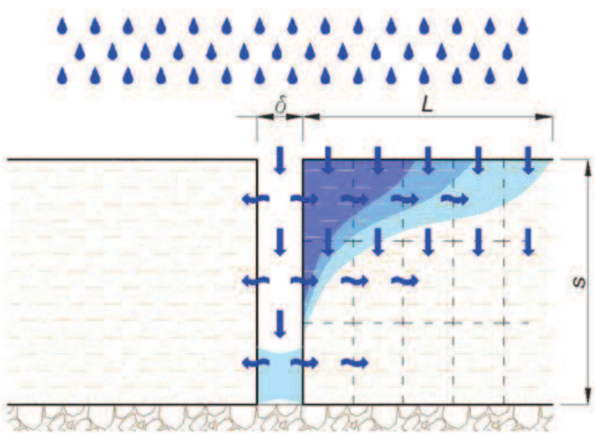

Fig. 1 – Schematic representation of the proposed dual-permeability model (from GALEANDRO & SIMEONE, 2012, modified).

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THE MODEL

In the proposed dual-permeability model, water flow in the matrix is described using the two-dimensional Richards equation. The flow rate (cm^3/s) in the fractures is obtained as the difference between the fracture inflow rate and the amount of water laterally adsorbed by the matrix, which is evaluated depending on the amount of water available in fractures and the saturated hydraulic conductivity of the soil (Fig. 1).

Matrix swelling is evaluated assuming a linear relationship between the matrix volumetric water content and the soil volume, assuming that the maximum swelling at full saturation is 2% of the initial volume.

The model additionally implements a capillary barrier below the base of the surficial fractured soil. Water accumulates in cracks up to a maximum capillary height, while in matrix above the interface between layers until the reaching of a critical pressure head.

THE CASE STUDY

As case study it has been considered a fractured loamy soil layer overlying a coarse sand. Fractures network and matrix features are summarized in Figure 1 and Table 1. The system has been discretized into soil elements of small dimensions (2 cm × 2 cm).

TABLE 1

Features of fractures, parameters for the upper soil texture (data from CARSEL & PARRISH, 1988) and for the lower layer (data from STORMONT & MORRIS, 1998).

Fractures	
spacing L (cm)	80
Half opening δ (cm)	1
Thickness s (cm)	150
Upper layer (loam)	
Residual water content θ_{res} (m^3m^{-3})	0.078
Saturated water content θ_{sat} (m^3m^{-3})	0.43
Saturated hydraulic condutivity K_{ms} (cm/s)	2.9 10^{-4}
Initial pressure head h_{init} (cm)	-1000
α (van Genuchten 1980) (cm^{-1})	0.036
n (van Genuchten 1980)	1.56
Lower layer (coarse sand)	
Water entry pressure head (mm)	200

The model has been used to simulate 3 rainfall event scenarios of different intensity and duration (Tab. 2), characterized by the same total rainfall height of 50 mm at the end of the rainfall events.

RESULTS AND DISCUSSION

The behavior of the system has been analysed in terms of water content and pressure head distributions, crack closure dynamics, and the capillary barrier breakthrough process during the two events (Figs. 2 and 3).

WATER CONTENT AND PRESSURE HEADS DISTRIBUTIONS

The presence of fractures in soils significantly accelerates water flow and affects the dynamics of water content/pressure heads distribution. The storage of water in the fractures and the matrix depends on the rainfall duration, crack opening, and functioning of the capillary barrier.

Initially, water starts to flow vertically in the matrix, involving only a few centimeters of the topsoil. If the rainfall intensity exceeds the hydraulic saturated conductivity of the soil, an amount of water goes in fractures and allow to activate the diffusion process from the fracture wall. Then, the flow into the matrix depends on the rainfall intensity, on the flow in the fractures and on the swelling process, which could close fractures.

During low intensity rains (i.e., 5 mm/h, event A), rainfall water entirely infiltrates vertically into the matrix and there is no storage of water in the fractures and lateral inflow into the matrix. At the end of rainfall event A, the first 8 cm of soil becomes almost saturated (Fig. 2a).

TABLE 2

Rainfall events: intensities, durations and corresponding inflow rate in fractures.

Rainfall event	Rainfall intensity (mm/h)	Duration (h)	Inflow rate for half a fracture (cm^3/s)
A	5	10	0
B	20	2.5	0.011
C	50	1	0.044

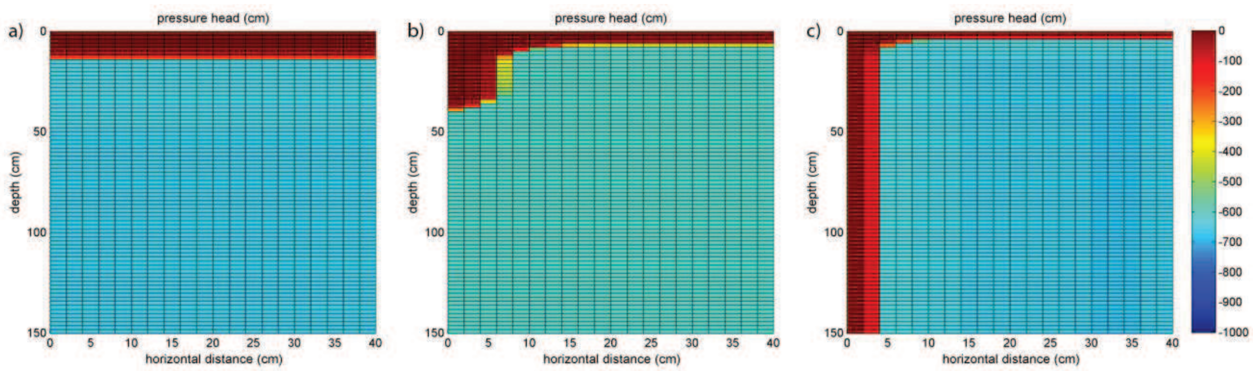

Fig. 2 – Pressure head distributions at the end of the considered meteoric events: a) Event A (5 mm/h, 10 h); b) Event B (20 mm/h, 2.5 h); c) Event C (50 mm/h, 1 h).

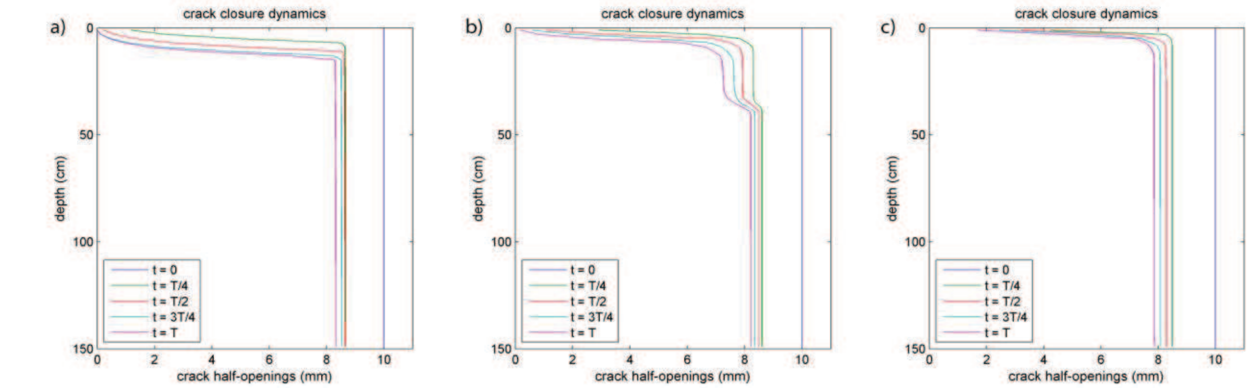

Fig. 3 – Crack closure dynamics: a) Event A (5 mm/h, 10 h); b) Event B (20 mm/h, 2.5 h); c) Event C (50 mm/h, 1 h).

For the intermediate rainfall intensity event (i.e., 20 mm/h, event B), water can flow through fractures, but does not reach the bottom of the surface layer. At the end of event B, horizontal water absorption involves 16 cm of the upper soil close to the fracture surface (Fig. 2b).

For the shorter and more intense precipitation (i.e., 50 mm/h, event C), water flows fast through fractures and instantaneously reaches the bottom. The diffusion process involves a very thin portion of the soil matrix (only about 8 cm close to the surface and 4 cm at greater depths) from the interface fracture/matrix (Fig. 2c).

Different rainfall intensities produce different water content distributions at the end of the rainfall events. Water is more uniformly distributed in the soil matrix for low-intensity and longer events than for shorter and high-intensity precipitation. The average degree of saturation in the first 30 cm of the upper soil layer is equal to 47% for the event A (5 mm/h), 41% for the intermediate event B, while it is only about 28% for the event C.

CAPILLARY BARRIER

The capillary barrier never breaks in matrix for the considered rainfalls, while the breakthrough of the capillary barrier below the fracture happens only for the event C (50 mm/h) when rain water can quickly flow down towards groundwater. The breakthrough occurs already after 30 seconds (corresponding to the rainfall of 0.42 mm) and allows water to flow quickly through the fine layer towards the coarse one.

SWELLING AND CLOSURE DYNAMICS

The process of crack closing starts at the soil surface and then propagates downwards toward the bottom of the surface soil layer. Crack closing dynamics is controlled by the rainfall intensity and duration. Crack closing is quite irregular for all the rainfall events. The horizontal water absorption contributes to the swelling and the closure of surface cracks, especially for the intermediate rainfall event B (20 mm/h). Deeper parts of the loamy soil are reached by a small amount of infiltrating water, so that the cracks opening at the bottom of the surface soil layer remains quite equal to the initial value (1 cm). For high-intensity precipitations (events B - C), the swelling process is less relevant than the event A, for which crack completely closes themselves after about 7 hours (Fig. 3).

CONCLUSIONS

The paper proposes a new dual-permeability model for the analysis of infiltration processes in fractured swelling soil. The model has been used to analyze infiltration processes in a fractured and swelling loamy soil overlaying a coarse sand soil for different rainfall events. Results show how for intense precipitations, vertical flow in fracture reaches fast significant depth, while for weak precipitations it could not happen or involve a smaller portion of the topsoil (about 40 cm). The swelling of soil elements is always irregular, leading to a differentiated swelling concentrated at the topsoil with almost complete crack closure for the low-intensity rainfall. Results also show how only for intense rainfalls, capillary barrier breaks-out only in fractures in a very short time.

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