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Unsaturated infiltration model to loess soils

Modèle de l'infiltration non saturé aux sols loess

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ABSTRACT
In many geoenvironmental problems the interpretation of infiltration process involves flow analysis through unsaturated porous media. Under conditions of unsaturated behavior soil permeability is a variable related to suction or volumetric water content. This work shows infiltration tests results conducted in laboratory. Tests were conducted on natural and compacted samples of silty clay soils that belong to loess formation in the center of Argentina. A finite-difference computer program was employed to simulate unsaturated transient flow. Advance of wetting front and seepage through natural and compacted soils have been simulated. Simulations results agree reasonably well with the data from laboratory tests. The present model has been used to simulate a silty clay liner behavior. Recommendations for liners landfills design located on regional little towns are formulated based on simulations obtained.

RÉSUMÉ
Dans beaucoup de problèmes en géotechnique de l'environnement l'interprétation de processus de l'infiltration implique l'analyse du flux à travers le média poreux non saturés. De perméabilité du sol sous comportement non saturé est une variable en rapport avec succion ou teneur en eau volumétrique. Ce travail montre résultats de l'épreuve de l'infiltration effectuée dans laboratoire. Les épreuves ont été effectuées sur échantillons de sols limons argileux naturel et a rendu compact qui appartiennent à formation du loess dans le centre d'Argentine. Un programme informatique de la différence fini a été employé pour simuler le flux transitoire non saturé. A été simulés l'avance de devant de mouiller et infiltration à travers de sols naturel et a rendu compact. Les résultats des simulations sont d'accord raisonnablement bien avec les données d'épreuves du laboratoire. Le modèle présent a été utilisé pour simuler un comportement de la barrière de sols limons argileux. Basé sur simulations obtenues son formulées recommandations pour dessin des barrières dans les dépôt de déchets localisé les petites villes régionales.

1 INTRODUCTION

Loess deposits cover about tenth part of continental earth surface. Usually are located in arid and semiarid regions. The Argentinean deposit is one of the most important in the southern hemisphere with a thickness in average of 30 meters. Generally these soils have been transported by winds to the deposition place (Teruggi, 1957). Loess soils located in the central area of Argentina belong to the Pampean formation and cover about 600,000 Km^2. Large part of Cordoba County is covered with loess deposits (Moll and Rocca, 1991).

Argentinean loess has a particular mineralogical composition. The main constituents of sand and silt fraction are plagioclases, quartz, volcanic glass and feldspars. In clay fractions, the main minerals are montmorillonite and illite. Calcium carbonate is found in two forms; as concretions or precipitated at particle contacts (Teruggi, 1957; Moll and Rocca, 1991).

The Hydraulic conductivity of loess depends on soil structure and presents anisotropy. As that could experience high volumetric changes due to collapse when is loaded or wetted, it is difficult to evaluate (Rocca, 1985). The need of hydraulic parameters definitions is determined by the utilization of these soils in many geotechnical constructions. Liner for sanitary landfills is a common solution for little and middle towns in Cordoba County. Some required properties for liners are proposed by internationals research. Mitchell and Jaber (1990) have reported required properties of clay liners. Benson et al. (1994) have showed how basic soil properties and compaction conditions monitored during the construction quality control of soil liners are related to hydraulic conductivity. Local constructions of landfills are not regulated by clear normative.

In this work results of hydraulic properties tests are presented. These results are used in simulating models of unsaturated soil behavior. Seepage conditions are discussed through advance of wetting front in depth. Recommendations for liners designs on these soils are formulated.

2 MODELING OF FLOW IN UNSATURATED SOILS

The studied case is a typical one-dimensional transient flow problem in unsaturated porous media. The problem is governed by Richard's partial differential equation (Richards, 1931)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K_\psi \frac{\partial(\psi + z)}{\partial z}\right] \tag{1}$$

where, θ = volumetric water content; ψ = matric suction; K_ψ = unsaturated hydraulic conductivity; z = coordinate and t = time.

Direct measures of unsaturated hydraulic conductivity function are complex. An alternative is the execution of infiltration laboratory tests and later indirect definition of associated parameters. Flow modeling process compared with experimental results are indicated in Wilson (1997), Choo and Yanful (2000).

In this study the Unsaturated Water and Heat Flow software, UNSAT-H, has been employed. It was developed at Pacific Northwest Laboratory in Richland, Washington (Fayer, 2000). UNSAT-H is a one-dimensional model and does not compute lateral drainage. The software solves equation (1) by finite-difference technique. Input data are soil properties and boundary conditions.

Khire et al. (1999) have performed water balance models on capillary barrier used as final covers of municipal solid waste landfill in semiarid regions. In loess soils, Zeballos and Terzariol (2002) have performed seepage under different compaction conditions and Terzariol et al. (2003) have compared modeling process with field tests. Results were very sensitive to the saturated hydraulic conductivity (Ks) between other variables.

3 SOIL DESCRIPTION

Soil used in the testing program is representative of soil in the central area of Argentina. It is a low plasticity silty clay soil designated as CL-ML in Unified Soil Classification System (USCS). Their properties are summarized in Table 1.

Table 1: Properties of soil

Variable	Unit	Value
Liquid limit	[%]	26.9
Plasticity index	[%]	3.9
Fines (particle < 0.074 mm)	[%]	95
USCS class (ASTM D-2487)		CL-ML
Dry unit weight, γ_d	[kN/m^3]	12.9
Max dry unit weight, $\gamma_{d\,max}$ (AASHTO-T99)		17.4
Optimal moisture, ω_{op} (AASHTO-T99)		17.5
Specific gravity, G_s		2.65

Previous studies have been employed for some variable definitions. Hydraulic conductivity for natural and compacted loess soils are contained in Francisca et al. (1998). For natural soil the saturated hydraulic conductivity (Ks) is 1.2×10^{-7} m/s. Saturated conductivity for compacted soil are around 1.5×10^{-9} m/s. Standard Proctor compactive effort (AASHTO-T99) and optimum water content was used (Figure 1).

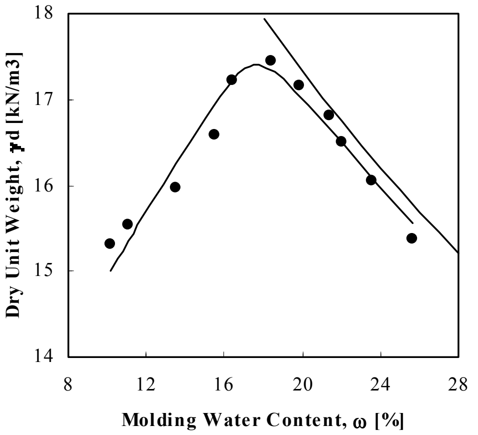

Figure 1. Standard Proctor compaction curve for Cordoba silty clay

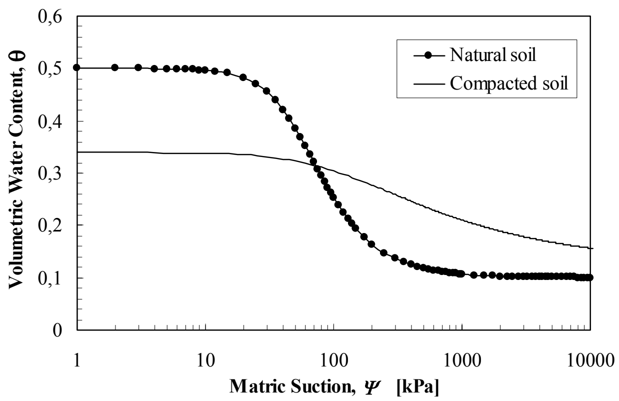

Figure 2. Soil-water characteristic curves for Cordoba silty clay

Soil-water characteristic curve (SWCC) for natural loess soils is defined in Aiassa et al. (2004). Natural silty clay soils were characterized by suction controlled cell and with similar soils reported in data base UNSODA (Leij et al., 1996). Rinaldi (2002) described soil-water characteristic curve for compacted loess soils. These results and UNSODA filtrate were considered. van Genutchen (1980)-Mualem (1976) unsaturated hydraulic conductivity function and SWCC equation were used. SWCC for drying process is shown in Figure 2.

4 INFILTRATION TESTS

Laboratory infiltration tests were realized using undisturbed and remolded samples. During tests one-dimensional flow was evaluated under constant hydraulic gradient. Cumulative infiltration was measured until steady-state flow condition was achieved. Infiltration tests were conducted in a cylindrical rigid wall cell with an inside diameter of 102 mm and a height of 105 mm (Figure 3). Similar cell has been employed for clay soils in Wang and Benson (1995). The top plate includes a port for venting gases and a port for inflow. A Mariotte bottle was installed to the inflow line to maintain a constant head. The bottom plate has a central port for outflow. Porous stones at the top and bottom complete the system.

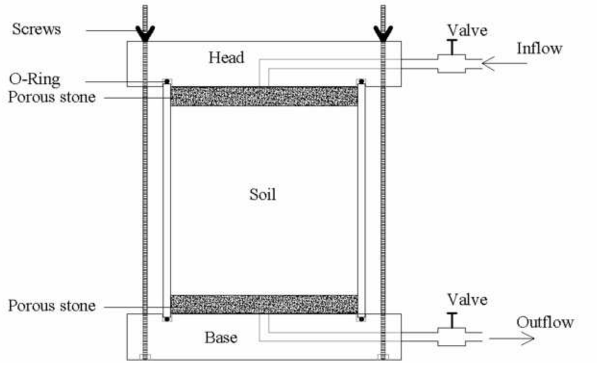

Figure 3. Infiltration cell

Table 2: van Genutchen (1980)-Mualen (1978) function parameters

Variable	Unit	Natural soil	Compacted soil for 100% T-99
Initial suction	cm	1000	1100
Saturated water content, θ_s	cm^3/cm^3	0.50	0.34
Residual water content, θ_r	cm^3/cm^3	0.10	0.12
Parameter, p	1/cm	0.0018	0.0009
Parameter, n		2.41	1.40
Saturated permeability, K_s	m/s	1.2×10^{-7}	1.5×10^{-9}
	cm/h	0.043	5.4×10^{-4}

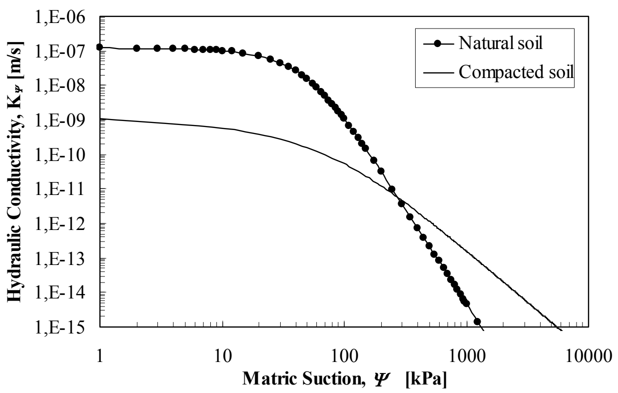

Figure 4. Unsaturated hydraulic conductivity functions for natural and compacted silty clay of Cordoba

Undisturbed samples were cut in cell. Soil-cell space was sealed to prevent preferential flow. Remolded samples were compacted in cell. Constant head top applied was 0.15 kPa.

Soil water characteristic curve parameters are indicated in Table 2. Figure 4 shows permeability functions obtained. Comparisons between measured and simulated infiltration tests are shown in Figure 5. Trends in laboratory data are reproduced by the model and agree reasonably well. Figure 6 and 7 compare the advance of wetting front for undisturbed and compacted samples of Cordoba silty clay.

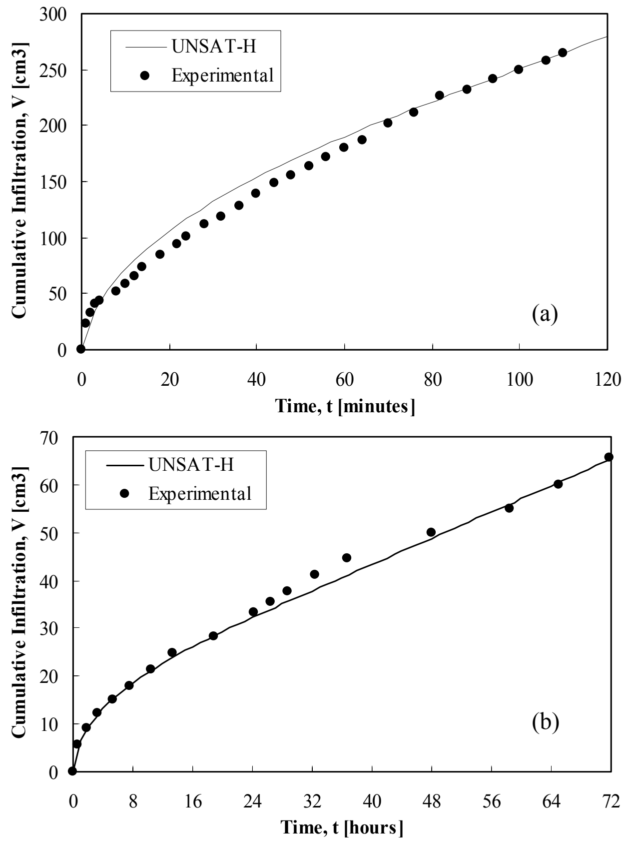

Figure 5. Cumulative infiltration versus time for Cordoba silty clay (a) natural soil (b) compacted soil

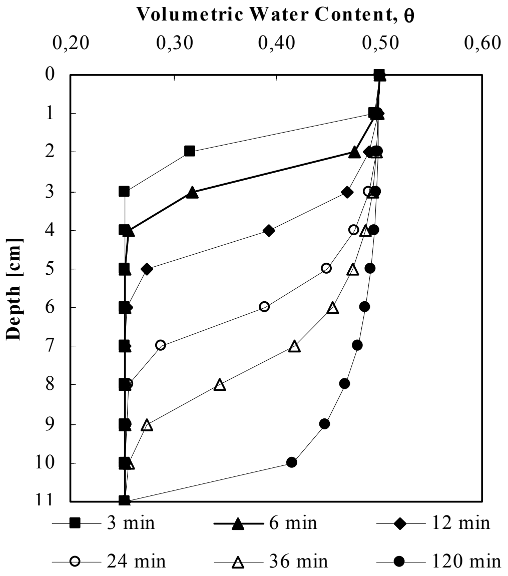

Figure 6. Volumetric water content profile for natural silty clay

Complementarily, a sensitivity numerical analysis of principal variables has been made. Range of variables belongs to appropriate limits for this soil. Sensitivity analyses have shown that saturated hydraulic conductivity (Ks) affect the infiltration rate considerably. Initial matric suction and soil water characteristic curve parameters, *p* and *n*, have a moderate influence. Constant head top almost does not affect infiltration curve. This suggests that, for these tests, matric suction dominates infiltration process, being significantly more important than hydrostatic pressure head or gravity head (Wang and Benson, 1995).

Results obtained allow some additional considerations. The wetting front is clearly defined for undisturbed samples. Contrarily, in compacted samples gradual variations are presents since tests start. The rates of advance of wetting front are different. For undisturbed samples is an order faster than compacted samples.

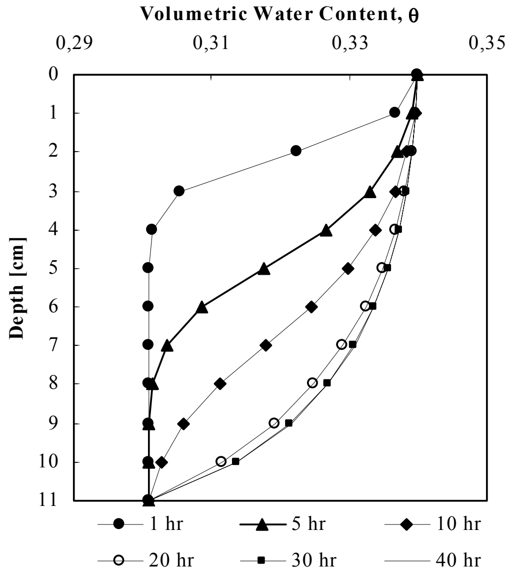

Figure 7. Volumetric water content profile for compacted silty clay

5 LINERS MODELING

Results have been used for the analysis of a silty clay landfill liner. Typical compaction conditions and thickness of 1.0 meter in liners have been considered. Seepage conditions imposed were; constant head top of 30 cm (3 kPa), surface saturation and no evaporation. Head top of 3 kPa is the maximum acceptable for actual international regulations (Qian et al., 2004).

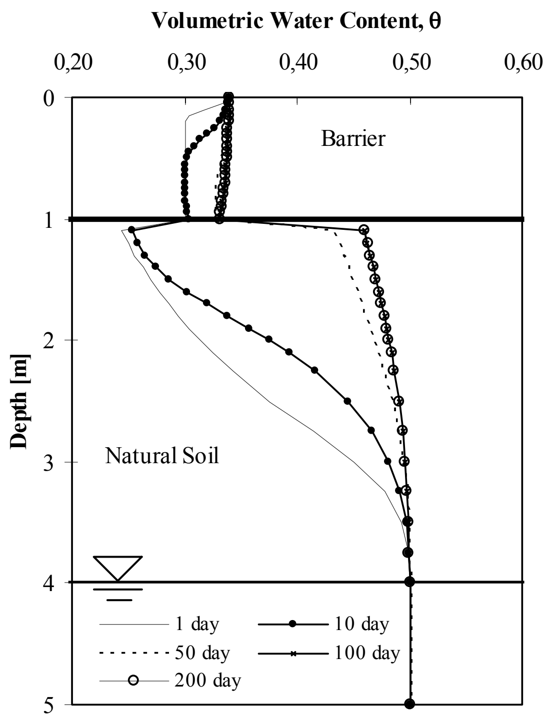

Figure 8. Volumetric water content profile for water table condition 1

Water table has been considered in two positions. In condition 1 is located at 3.0 meters under bottom liner. Here, a linear variation for matric suction was assumed. Boundary conditions imposed for matric suctions were 0 kPa on water table and 110 kPa on natural soil-liner interface. In condition 2 water table was considered 20 meters under bottom liner. Variation of matric suction and boundary conditions were considered in a similar way that in condition 1.

Infiltration simulation for condition 1 shows that steady-state flow was achieved in 175 days, with a cumulative infiltration of 4.8 centimeter (cm) and an instantaneous infiltration rate of 6.53×10^{-4} centimeter per hour (cm/h). For condition 2 it was achieved in 590 days, with a cumulative infiltration of 14.5 cm and an instantaneous infiltration rate of 8.89×10^{-4} cm/h.

Medium rate of infiltration in condition 1 was 0.027 cm/day and in condition 2 it was 0.025 cm/day. A similar result obtained for both conditions is attributed to steady-state flow.

Evolutions of volumetric water content profile for both conditions are shown in Figure 8 y 9. Results are influenced by water table positions. For condition 1 natural soil saturation is achieved in around half year. This condition combines environmental and collapse problems. Despite this, in condition 2 saturation levels are low, still for steady-state flow.

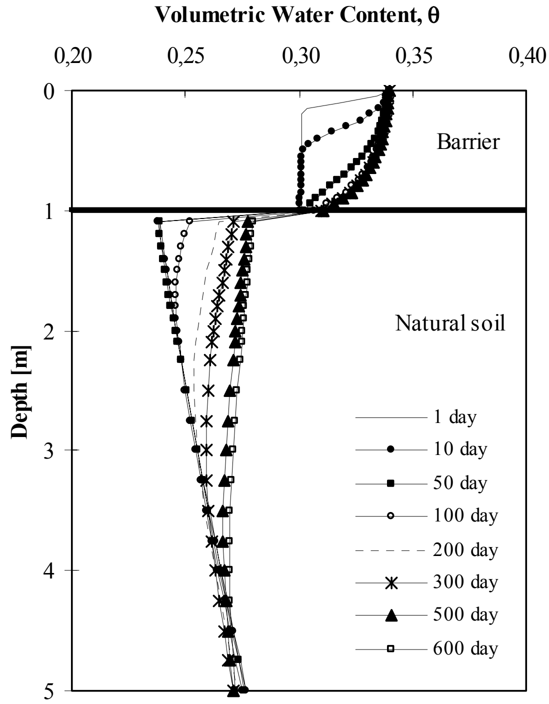

Figure 9. Volumetric water content profile for water table condition 2

6 SUMMARY AND CONCLUSIONS

Cumulative infiltration and advance of wetting front in natural and compacted loess soils have been studied considering unsaturated soil behavior concepts. Laboratory tests results and indirect procedures were used. Simulations results agree reasonably well with laboratory results. This validates the variable identification methods. Little divergences are attributed to secondary variable control during tests and parameters adopted.

Experimental results have been employed to simulate landfills liners behavior in loess soils. Infiltration and advance of wetting front in landfill liners were evaluated. Modeling results have shown that water table have a strongly influence on behavior of these structures. Water table close to liner reduces the time needed to obtain steady-state flow conditions and an instantaneous infiltration rate. In this case, collapse behavior must be considered for high saturation. Water content increase to obtain steady-state flow depends on the water table position. When water table is deep, steady-sate flow produces a low increase in water content of natural soil. In this situation the risk of structural collapse of natural soil is reduced.

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