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Hysteresis: Phenomenon and Modeling in Soil- Water Relationship

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ABSTRACT-Hysteresis has been widely recognized in the soil water relationship. In this paper, a detailed review of hysteresis was performed in relation to its models. So far, different models have been suggested to describe hysteresis in the water retention curve (WRC) that could be categorized into two main groups: *conceptual* and *empirical* models. The models in the first group are based on the domain theory of capillary hysteresis and those in the second group rely on the analysis of observed WRC shape and properties. *Conceptual* models include the *independent* and *dependent domain theories* and the *Parlange's model*, while *empirical* models consist of the *interpolation, linear, Slope* and *Scaling down* models. Different results of studies carried out by several researchers showed that the *Parlange* model, that uses the concept of rational extrapolation, was the best model to predict hysteresis of the WRC.

Keywords: Conceptual Model, Empirical Model, Hysteresis, Parlange Model

INTRODUCTION

The description and prediction of water flow through unsaturated soils imply an understanding of unsaturated soil properties. The main unsaturated soil properties used in engineering calculations are the relationships between suction (or water pressure), ψ, (cm of water or kPa) and volumetric water content, θ, (cm^3/cm^3) as well as that between suction and hydraulic conductivity, K. These two relationships comprise the *water retention curve* (WRC) and permeability function, respectively. Due to the complex nature of the liquid-phase configuration in an unsaturated porous medium, the relationship between water pressure and water content is not unique and presents hysteresis effects (e.g. 14, 43, 52 and 5). As shown in Figure 1, a soil typically shows a volumetric water content that is less for a wetting process (such as infiltration) than for a drying process (such as evaporation or drainage) at a given water pressure.

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The hysteresis effect can be attributed to 4 main causes (e.g. 18 and 37): a) geometric nonuniformity of individual pores, resulting from the so called "Ink Bottle" effect, b) different spatial connectivity of pores during drying or wetting processes, c) variation in the liquid-solid contact angle, where the contact angle and the radius of curvature are greater in the case of an advancing meniscus than the case of a receding one. A given water content will, therefore, tend to exhibit greater suction in desorption than sorption, and d) air entrapment, which further reduces the water content of newly wetted soil. Failure to attain true equilibrium (though not, strictly speaking, true hysteresis) can accentuate the hysteresis effect.

The two complete characteristic curves, from saturation to dryness and vice versa, are the *main branches* of the hysteretic soil moisture characteristics. When a partially wetted soil commences to drain, or when a partially desorbed soil is rewetted, the relation of suction to moisture content follows a number of intermediate curves as it moves from one main branch to the other. Such intermediate spurs are called *scanning curves*.

In the past, hysteresis was generally disregarded in the practice of soil physics. This may be justifiable in the treatment of processes involving monotonic wetting (e.g., infiltration) or monotonic drying (e.g., evaporation). Nevertheless, hysteresis may be important in cases of composite processes where wetting and drying occur simultaneously or sequentially in various parts of the soil profile (e.g., redistribution). Two soil layers of identical texture and structure may be at equilibrium with each other (i.e., at identical energy states) and yet may differ in wetness if their sorbing-desorbing histories have been different. Furthermore, hysteresis can affect dynamic, as well as static properties of the soil (i.e., hydraulic conductivity and flow phenomena).

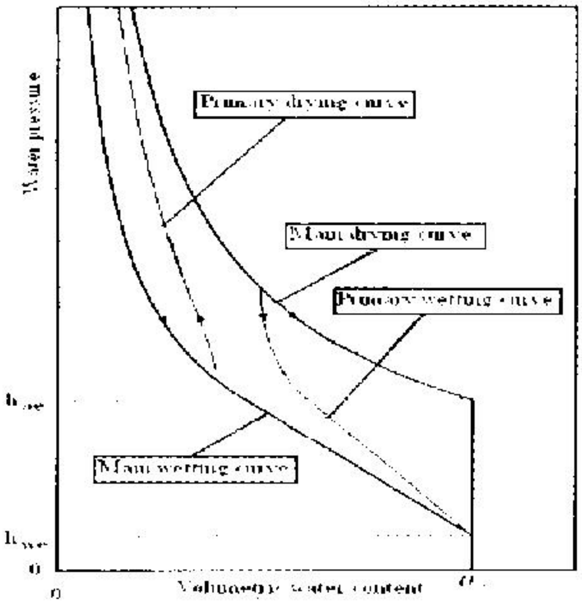

Fig. 1. Schematic representation of water retention curves with hysteresis effects

Because of the important effects of hysteresis on most soils, especially coarse-textured soils (18), different models have been developed to describe different hysteresis curves (main, primary and secondary curves) of the WRC over the last 40 found that the simplified model leads to better results than the models based on independent domain model theories for soils having a major portion of their hysteresis loop in the range of air entry value. However, the better performance of *Model III* was achieved at the expense of using more measured data (it requires a primary drying scanning curve in addition to the main hysteresis loop for calibration) and detraction from the simplicity of the model.

Mualem (31) modified the dependent domain theory. The modified model corrects the moisture content changes calculated on the basis of the independent domain ($\Delta\theta_0$) by multiplying these changes with a correction factor $P_d(\theta)$:

$$P_d(\theta) = \frac{\theta_s(\theta_s - \theta)}{(\theta_s - \theta_w(\psi^+))^2} \tag{8}$$

where ψ^+ is the potential for which $\theta_d(\psi^+) = \theta$. For a wetting curve of order *n* the correction factor is $P_d(\theta(\psi_n)), \psi_n$ being the pressure head of the *n-th* reversal point. For a drying curve the factor is $P_d(\theta(\psi))$, where ψ is the current pressure head for which the moisture content is being calculated. This implies that for a drying curve P_d is to be calculated iteratively, hence the implicit character of the model. Computed primary and secondary scanning curves derived by this model showed good agreement with measured data. The results are compared with computed curves based on *Model II* of Mualem (29). The new model seems to agree with observation much better that *Model II*, which uses the same amount of data for calibration.

Parlange's model

Parlange (39) developed a conceptual model which requires knowledge of one boundary instead of two boundaries, as in Mualem's case (31). In this model Parlange (39) assumed that the distribution function is only the function of ψ_d:

$$f(\psi_d, \psi_w) = f(\psi_d) \tag{9}$$

Furthermore, Parlange (39) pointed out that in the determination of the moisture retention characteristics the actual wetting boundary curve is seldom obtained. This implies that only uneven order drying and even order wetting scanning curves can be measured.

To understand the principle of Parlange's model (39), consider a drying scanning curve starting at potential ψ_1 on the wetting boundary of the curve. Then:

$$\theta_d(\psi, \psi_1) = \theta_w(\psi) + \int_{\psi_1}^{\psi} d\psi_w \int^{\psi_w} f(\psi_d, \psi_w) d\psi_d \tag{10}$$

Which correspond to the domain of integration shown in Fig. 2, where $|\psi_M|$ is a reasonable maximum suction. If *f* is a function of ψ_d only, then:

$$\theta_w = \int_{\psi}^{\psi_M} d\psi_w \int_{\psi}^{\psi_w} f(\psi_d) d\psi_d \tag{11}$$

and

$$\theta_d(\psi, \psi_1) = \theta_w(\psi) - (\psi - \psi_1)\left(\frac{d\theta_w}{d\psi}\right)_\psi \tag{12}$$

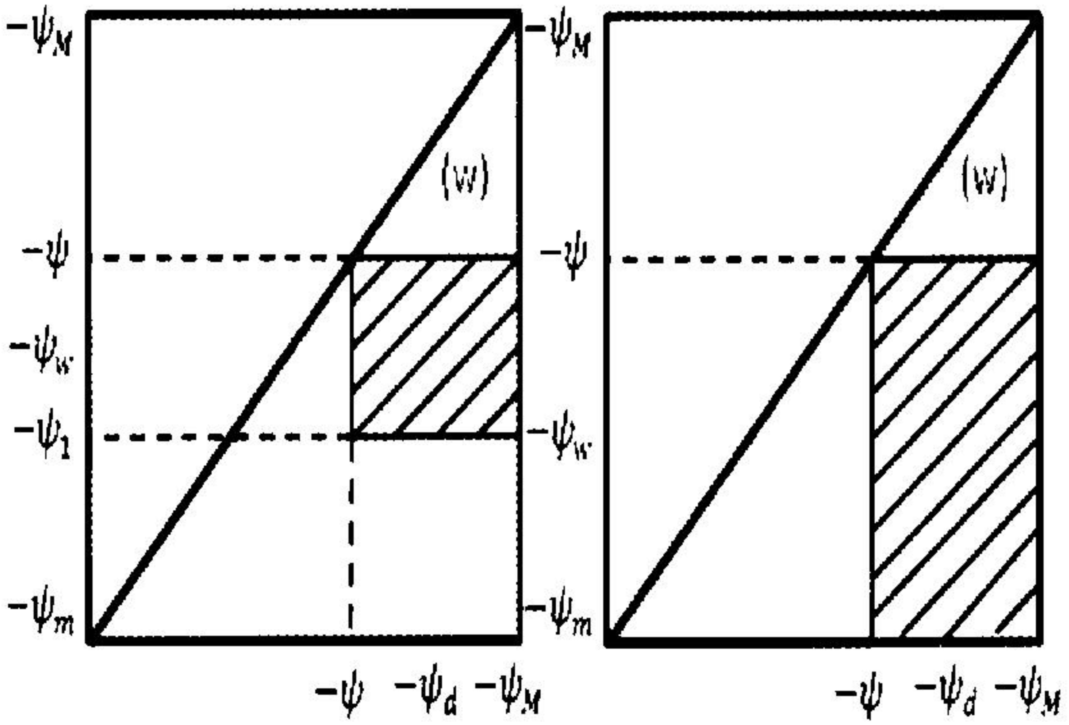

Fig. 2. Domains of integration for the function f in Eq. (11) and (14), as given by crosshatched rectangles for the drying (left) and wetting (right) scanning curves. The triangle (w) is the domain of integration of *f* defining θ_w in Eq. (12). If an opening becomes empty during the drying process (left), i.e., for $-\psi_1 < -\psi_d < -\psi$, then the attached pore is also emptied, since the openings are smaller than the pores. If the suction decreases during wetting (right), all corresponding pores are filled, since their smaller openings are automatically filled; in addition, pores of any size that have openings so small that the latter were never dried, i.e., for $-\psi_d > -\psi_2$, remain filled

Similarly, a wetting scanning curve starting at potential ψ_2 on the drying boundary of the loop is given by:

$$\theta_w(\psi, \psi_2) = \theta_w(\psi) + \int_{\psi_m}^{\psi} d\psi_w \int_{\psi_2}^{\psi_M} f(\psi_d, \psi_w) d\psi_d \tag{13}$$

which corresponds to the domain of integration shown in Fig. 1, where $|\psi_M|$ is a reasonable minimum suction, normally close to zero, or when f is a function of ψ_d only,

$$\theta_w(\psi, \psi_2) = \theta_w(\psi) - (\psi - \psi_m)(\frac{d\theta_w}{d\psi})_{\psi_2} \tag{14}$$

If the drying boundary is given by (13) with $\psi_1 = \psi_m$, then $\theta_w(\psi, \psi_2)$ in (14) together with the boundary condition $\theta_w(\psi_2, \psi_2) = \theta_d(\psi_2, \psi_m)$ can be used in (12) instead of $\theta_w(\psi)$. This result is easily verified by direct substitution.

Comparison with experiments has showed that if the shape of the drying scanning curves varies smoothly, then the drying boundary of the loop was indeed was applied to describe the hysteresis effects in the water retention curve by O'Kane et al. (37), using the concept of a continuous analog of a finite parallel connection of relays. The Haverkamp et al. (17) model, based on geometric scaling, was recently modified and simplified (12). Another hysteresis empirical model was developed for sandy soils using the basic concept of shape similarity between the WRC and the cumulative particle-size distribution function (16). In this case, the hysteresis is predicted from the basic properties of the soil, not from a WRC.

Summary and Comparison of models

Two main group of hysteresis models were reviewed in connection to their theories. These models were categorized into *conceptual* and *empirical* models. The first group is based on the domain theory of capillary hysteresis and the second group relies on the analysis of observed WRC shape and properties. *Conceptual* models included the *independent and dependent domain theories* and *Parlange's model*, while *empirical* models consisted of the *interpolation*; *linear*; *Slope* and *Scaling down* models. Several authors have compared these different models. Viaene et al. (54), following a statistical analysis of hysteresis models, concluded that the best 2 branch models were conceptual models (Mualem II and IV), while the Parlange model was selected as the best choice for hysteresis prediction using a single branch. The same conclusion was reached by Si and Kachanoski (49) about one branch models. However, Jaynes' comparison (21 and 22) led to the conclusion that none of the methods were consistently better than the others, even for the more complex models with more than two branches. Jaynes also concluded that the linear model (empirical type of model) appears to be the best approach to predict hysteresis. Maqsoud et al. (27) indicated that the Universal Mualem model did not predict the WRC adequately. However, the two versions of the Parlange model (22 and 3) allow for good predictions of the main drying curves. More recently, different studies (3 and 17) suggested that the Parlange model, that uses the concept of rational extrapolation, was the best model to predict hysteresis of the WRC. Bradock et al. (3) proposed a new formulation of the Parlange model using the Van Genuchten (53) equation instead of Brooks and Corey's (4). However, this version of the Parlange model should be examined in most texture soils.

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