POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)

URL: http://dergipark.gov.tr/politeknik

A formulation for scanning soil-water characteristic curves

Zemin-su geçiş karakteristik eğrileri için bir formülasyon

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Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article): Kenanoğlu M. B. ve Toker N. B., "A formulation for scanning soil-water characteristic curves", ***Politeknik Dergisi***, 21(4): 901-906, (2018).

Erişim linki (To link to this article): http://dergipark.gov.tr/politeknik/archive

DOI: 10.2339/politeknik.389619

Zemin-Su Geçiş Karakteristik Eğrileri İçin Bir Formülasyon

Araştırma Makalesi / Research Article

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(Geliş/Received : 10.08.2017 ; Kabul/Accepted : 08.01.2018)

ÖZ

Zemin–su karakteristik eğrisinin (ZSK eğrisi) histeretik doğası, deneysel veya literatürdeki uyum denklemleri ile elde edilebilen bakir ıslanma (su tutma) ve bakir kuruma eğrilerinin bir rejimden diğerine geçiş sırasındaki olası tüm değerleri sınırladığı varsayımı yapılarak elde edilmiştir. Bakir ZSK eğrileri arasındaki rejim değişimleri olan geçiş eğrileri geometriye dayalı ilişkilerle elde edilmiştir. Bu ilişkiler literatürde verilmiş çeşitli deney datasının şekilleri gözlemlenerek elde edilmiştir. Önerilen ilişkiler infiltrasyon ve buharlaşma gibi olaylar ile ilgili fiziksel problemlerin modellenmesinde artımlı olarak kullanılabilir. İlişkilerde verilen K parametresi için ampirik bir denklem önerilmiştir. Böylece geliştirilen denklemler ile sadece bakir kuruma ve ıslanma ZSK eğrileri ve rejim geçiş noktası kullanılarak geçiş eğrileri modellenebilir.

Anahtar Kelimeler: Zemin-su karakteristik eğrisi, su tutma eğrisi, geçiş eğrisi, histeresis.

A Formulation for Scanning Soil-water Characteristic Curves

ABSTRACT

The hysteretic nature of soil water characteristic curve (SWCC) is captured assuming the virgin drying and virgin wetting (a.k.a. imbibition) curves; which can be obtained from experiments or various fitting equations in the literature, bound all possible values during transition from one regime to the other. The scanning curves (transitions between virgin wetting and drying SWCC) are modelled by using geometry-based relations, which are devised by means of the observations on the shapes of graphs of experimental data found in the literature. The proposed relations can be used in incremental form to predict suction in different frameworks (e.g. infiltration, evaporation) and related physical problems. An empirical equation is proposed for power parameter (K), which is introduced in the relations. Only virgin wetting and virgin drying SWCCs and regime reversal point suffice to model a scanning curve in the developed formulations.

Keywords: Soil-water characteristic curve, retention curve, scanning curve, hysteresis.

1. INTRODUCTION

The relationship between the soil water pressure (suction) and water content is described by soil-water characteristic curve (SWCC) (also called "retention curve") for partly saturated soils. One of the most significant features of the SWCC is its hysteretic behaviour (Fig.1). The drying path (e.g. decrease of water content, usually due to evaporation) differs from the wetting path (e.g. increase of water content due to imbibition or infiltration). Experimental studies have shown closed hysteresis loops emerge between wetting and drying branches of the SWCC during variation of water content [1,2,3,4,5,6]. These transition curves are called scanning curves. The hysteretic nature of SWCCs complicates modelling of various unsaturated soil mechanics problems since there can be endless number of possible transition paths between virgin drying and virgin wetting curves depending on the wetting-drying history, initial water content and soil type.

Hysteresis models were proposed in the literature in order to trace scanning curves [7,8]. In this study, novel formulations for scanning curves were developed in the incremental form.

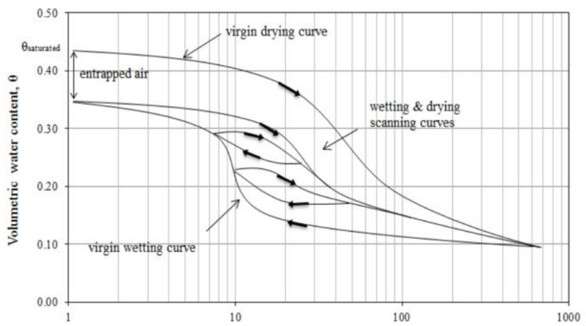

Figure 1. Schematic illustration hysteretic nature of SWCC and scanning curves.

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2. FORMULATION

The hysteretic nature of SWCC is captured assuming virgin drying and virgin wetting curves (which can be obtained from experiments or various fitting equations in the literature) bound all possible values following regime reversals. Two seperate formulas (one for drying and another for wetting) were developed for modelling of scanning soil-water characteristic curves. Formulas were developed by interpolation of a power of volumetric water content ratios over ratios of logarithms of suction, devised from the observations on the shapes of graphs of experimental data (Equ. 1).

$$\frac{a}{b} = \frac{c}{d}\left(\frac{e}{f}\right)^K \tag{1}$$

The point of regime reversal and a ultimate point constitute the extent of a scanning curve. The residual state of soil water is considered as ultimate point in case of drying; however, entrapment of air complicates defining a ultimate point during wetting. The ultimate point, which is between the saturated water content of virgin drying and maximum water content of virgin wetting SWCC, is determined by interpolation between these water content values of zero suction, based on regime reversal water content (Equ. 2).

$$\theta_{max} = \theta_{max,w} + \frac{\theta_{sat} - \theta_{max,w}}{\theta_{sat} - \theta_{res}}\left(\theta_{rr} - \theta_{res}\right) \tag{2}$$

where, θ_{max} is the maximum volumetric water content of wetting scanning curve, $\theta_{max,w}$ is the maximum volumetric water content of the virgin wetting curve, θ_{sat} is the drying saturated volumetric water content of the virgin drying curve, θ_{res} is the residual volumetric water content and θ_{rr} is the value of volumetric water content at the begining of this cycle of wetting.

For each point on the scanning curve, the suction values on the virgin drying and virgin wetting SWCC correspond to preceding and current water content are determined. Unknown suction value for current water content should lie in between these suction values and following relations are devised. The proposed relations are given in the form such that subscript j refers to temporal variation. In the following Fig.2 variables of the developed relations are illustrated.

The relation of scanning curve in the direction of wetting is given in equation [3].

$$\log(\psi_j) = \log\left(\psi_j^w\right) + \frac{\log\left(\frac{\psi_{j-1}}{\psi_{j-1}^w}\right)}{\log\left(\frac{\psi_{j-1}^d}{\psi_{j-1}^w}\right)}\left(\frac{\theta_{max} - \theta_j}{\theta_{max} - \theta_{j-1}}\right)^K \log\left(\frac{\psi_j^d}{\psi_j^w}\right) \tag{3}$$

where, $\log(\Psi_j)$ is the logarithm of unknown suction value at present, $\log(\Psi^w_j)$ is the logarithm of corresponding value of suction on virgin wetting curve for θ_j, Ψ_{j-1} is the value of suction at previous time step, Ψ^w_{j-1} is the corresponding value of suction on virgin wetting curve for θ_{j-1}, Ψ^d_{j-1} is corresponding value of suction on virgin drying curve for, θ_{j-1} ,θ_{max} is ultimate wetting saturated water content and it can be determined by using equation [2], θ_j is the water content at present condition, θ_{j-1} is the water content at previous condition, Ψ^d_j is the corresponding value of suction on virgin drying curve for θ_j, Ψ^w_j is the corresponding value of suction on virgin wetting curve for θ_j and K is the power-type parameter, which controls the flatness of the scanning curve. It should be noted that virgin drying and virgin wetting curves can be in the form of retention curve equations such as Van Genuchten (1980), [9].

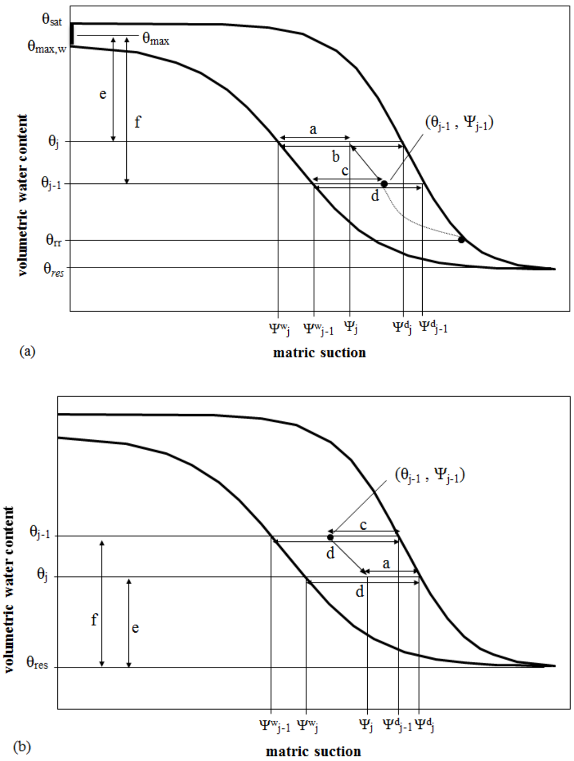

Figure 2. Schematic illustration of variables used in the formulations for wetting (a) and for drying (b).

Similarly, the scanning curve equation in the direction of drying is given equation [4].

$$\log(\psi_j) = \log\left(\psi_j^d\right) - \frac{\log\left(\frac{\psi_{j-1}^d}{\psi_{j-1}}\right)}{\log\left(\frac{\psi_{j-1}^d}{\psi_{j-1}^w}\right)}\left(\frac{\theta_j - \theta_{res}}{\theta_{j-1} - \theta_{res}}\right)^K \log\left(\frac{\psi_j^d}{\psi_j^w}\right) \tag{4}$$

2.1. Calibration of Proposed Hysteresis Model

Proposed scanning curve equations are fit onto experimental data found in the literature, using the power (K) as fitting parameter (Fig. 3-14). Least square regression method was used in the calculations. Coefficient of determination (R^2) values were determined by setting logarithm of suction values as independent variable in the regression analysis.

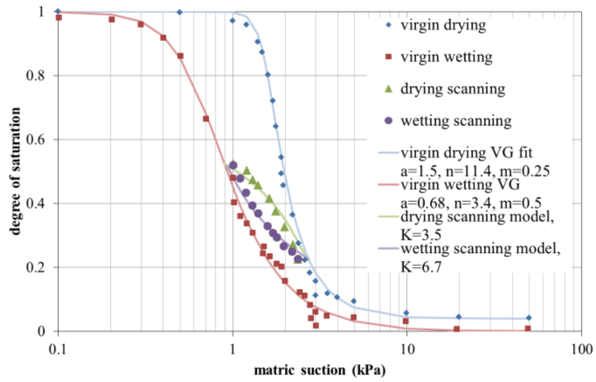

Figure 3. The proposed hysteresis model for a scanning loop (experimental data from [10]), the R^2 values for drying and wetting scanning curves are 0.890 and 0.917, respectively.

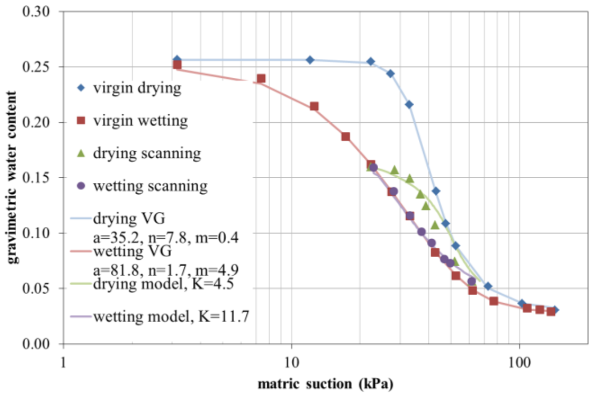

Figure 4. The proposed hysteresis model for a scanning loop (experimental data from [4]), the R^2 values for drying and wetting scanning curves are 0.924 and 0.993, respectively.

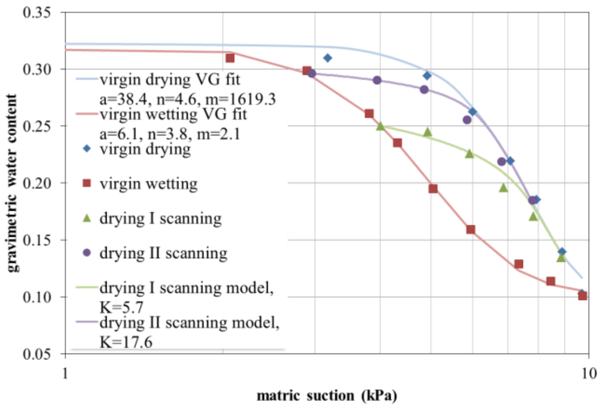

Figure 5. The proposed hysteresis model for drying scanning curves (experimental data from [11]), the R^2 values for drying I and drying II scanning curves are 0.970 and 0.992, respectively.

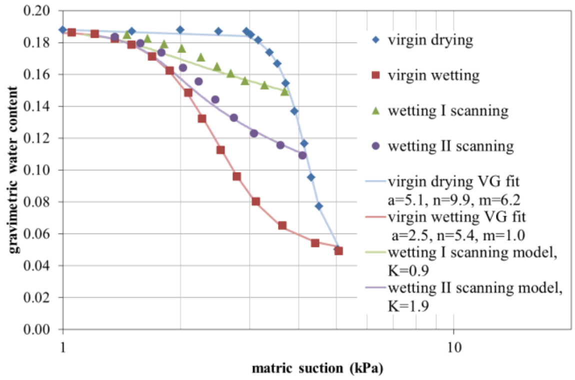

Figure 6. The proposed hysteresis model for wetting scanning curves (experimental data from [12]), the R^2 values for wetting I and wetting II scanning curves are 0.889 and 0.956, respectively.

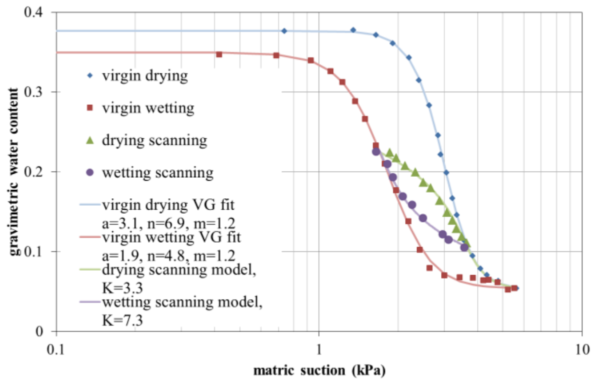

Figure 7. The proposed hysteresis model for a scanning loop (experimental data from [13]), the R^2 values for drying and wetting scanning curves are 0.980 and 0.991, respectively.

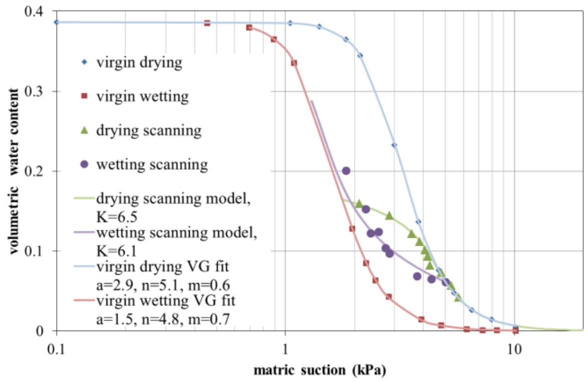

Figure 8. The proposed hysteresis model for a scanning loop (experimental data from [14]), the R^2 values for drying and wetting scanning curves are 0.956 and 0.923, respectively.

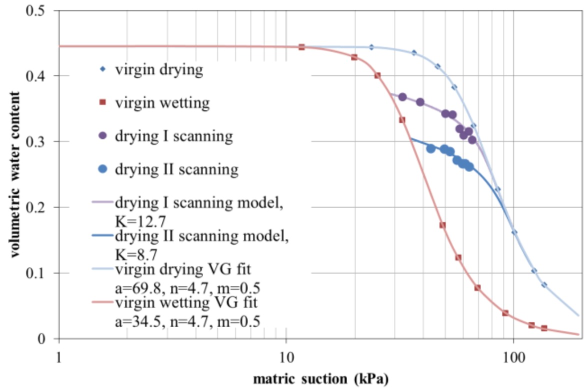

Figure 9. The proposed hysteresis model for drying scanning curves (experimental data from [15]), the R^2 values for drying I and drying II scanning curves are 0.935 and 0.822, respectively.

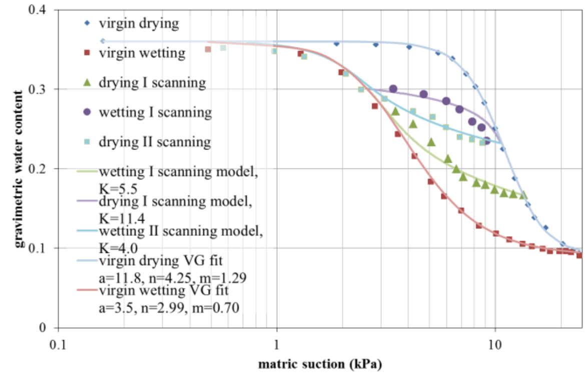

Figure 12. The proposed hysteresis model for scanning loop (experimental data from [17]), the R^2 values for wetting I, drying I and wetting II scanning curves are 0.929, 0.787 and 0.899, respectively.

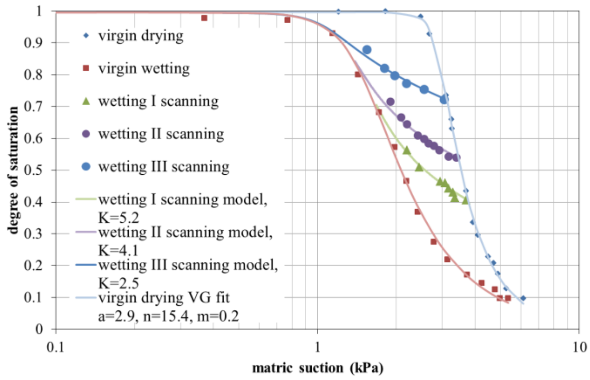

Figure 10. The proposed hysteresis model for wetting scanning curves (experimental data from [16]), the R^2 values for wetting I, wetting II and wetting III scanning curves are 0.958, 0.955 and 0.971, respectively.

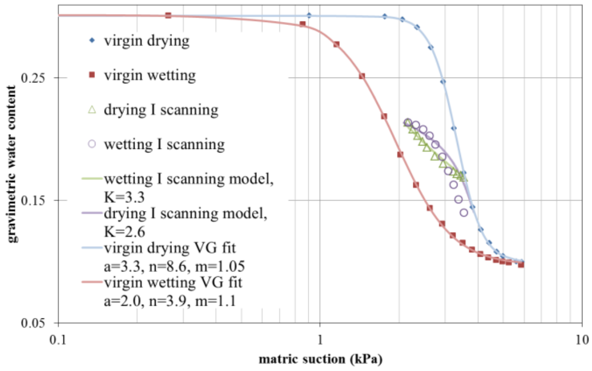

Figure 13. The proposed hysteresis model for scanning loop (experimental data from [17]), the R^2 values for wetting I and drying I scanning curves are 0.979 and 0.838, respectively.

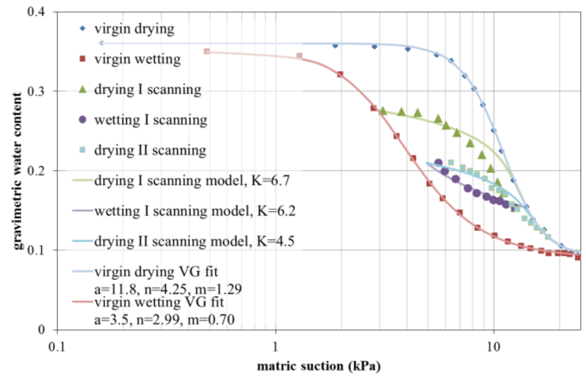

Figure 11. The proposed hysteresis model for scanning loop (experimental data from [17]), the R^2 values for drying I, wetting I and drying II scanning curves are 0.860, 0.908 and 0.901, respectively.

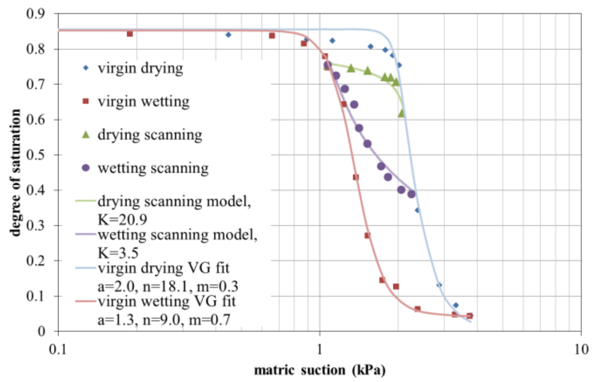

Figure 14. The proposed hysteresis model for a scanning loop (experimental data from [18]), the R^2 values for drying and wetting scanning curves are 0.979 and 0.934, respectively.

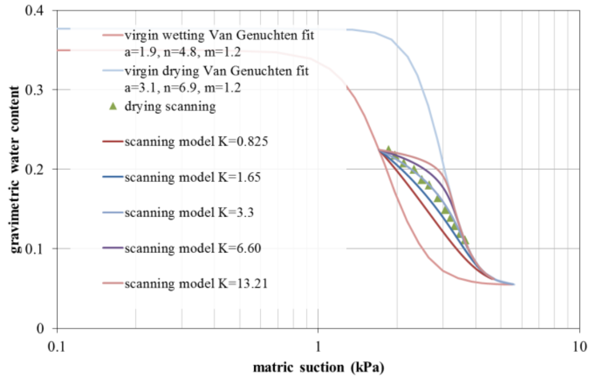

Figure 15. Sensitivity of scanning curves for parameter K (experimental data from [10]), the R^2 values for K=0.825, K=1.65, K=3.3, K=6.6 and K=13.21 are 0.548, 0.867, 0.980, 0.875 and 0.648, respectively.

The sensitivity of scanning curves to the power parameter *K* is investigated (Fig. 15). The variation of the power parameter, *K* only marginally changes the shape and accuracy of the generated scanning curves.

2.2. An Empirical Equation For Parameter *K*

The power parameter, *K* in the relations appears to depend on various properties, such as regime (drying or wetting), soil type and regime reversal water content (θ_{rr}). A relationship was found between the *K* and the ratio of the difference between θ_{rr} and the initial value of water content on the virgin curve of that regime direction (e.g. θ_{res} for wetting and θ_{sat} for drying) to the entire water content range of that virgin curve. An empirical equation based on this relationship was proposed to estimate *K* parameter for given soil (Fig. 16, Equ. 5-a for wetting regime and Equ. 5-b for drying

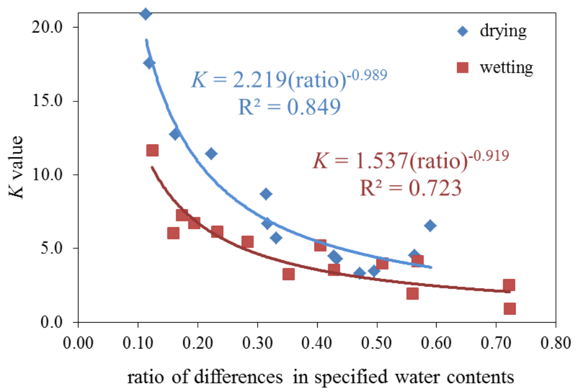

Figure 16. Proposed empirical equations for parameter *K*.

$$K = 1.537\left(\frac{\theta_{rr} - \theta_{res}}{\theta_{max,w} - \theta_{res}}\right)^{-0.919} \quad (5\text{-a})$$

$$K = 2.219\left(\frac{\theta_{sat} - \theta_{rr}}{\theta_{sat} - \theta_{res}}\right)^{-0.989} \quad (5\text{-b})$$

regime). Therefore, proposed scanning curve equations only require the two virgin soil-water characteristic curves and regime reversal water content value.

2.3. Validation

The proposed scanning curve equations (Equ.3, Equ.4, Equ.5-a, Equ.5-b) were validated by employing empirical equation for *K* parameter to fit experimental data. R^2 values of both least square fitting and empirical equation based fitting were listed in Table 1. It is seen that results are very close to each other in general.

Table 1. Comparison of R^2 values of least square fitting and empirical equation based fitting.

Reference	Regime	R^2 value (least square)	R^2 value (empirical)
Fig.3, [10]	Wetting	0.917	0.897
Fig.3, [10]	Drying	0.890	0.875
Fig.4, [4]	Wetting	0.993	0.993
Fig.4, [4]	Drying	0.924	0.924
Fig.5, [11]	Drying I	0.970	0.969
Fig.5, [11]	Drying II	0.992	0.991
Fig. 6, [12]	Wetting I	0.889	0.748
Fig. 6, [12]	Wetting II	0.956	0.941
Fig.7, [13]	Wetting	0.991	0.990
Fig.7, [13]	Drying	0.980	0.951
Fig.8, [14]	Wetting	0.923	0.897
Fig.8, [14]	Drying	0.956	0.901
Fig. 9, [15]	Drying I	0.935	0.933
Fig. 9, [15]	Drying II	0.822	0.724
Fig.10, [16]	Wetting I	0.958	0.858
Fig.10, [16]	Wetting II	0.955	0.822
Fig.10, [16]	Wetting III	0.971	0.946
Fig.11, [17]	Drying I	0.860	0.859
Fig.11, [17]	Wetting I	0.908	0.899
Fig.11, [17]	Drying II	0.901	0.901
Fig.12, [17]	Wetting I	0.929	0.926
Fig.12, [17]	Drying I	0.787	0.780
Fig.12, [17]	Wetting II	0.899	0.884
Fig.13, [17]	Wetting I	0.979	0.951
Fig.13, [17]	Drying I	0.838	0.728
Fig. 14, [18]	Drying I	0.979	0.905
Fig. 14, [18]	Wetting I	0.934	0.933

3. CONCLUSION

A formulation for scanning curves was developed, based on interpolation over logarithmic scale of suction and a variable exponent (*K*) of water contents. An empirical equation for *K* was devised, based on calibration against experimental data found in several sources from the literature. Consequently, only virgin wetting and virgin drying SWCCs and the point of regime reversal suffice to define the scanning curve. Equations [2], [3] and [5-a] can be merged to model wetting regime scanning curve, whereas equations [4] and [5-b] together define the drying scanning curve. The proposed relations can be used in incremental form to predict changing suction in different frameworks (e.g. elastoplastic constitutive models, infiltration and evaporation models) and related physical problems.

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