doi: 10.18720/MCE.77.13

Hysteresis of the soil water-retention capacity: estimating the scanning branches

Гистерезис водоудерживающей способности почвы

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Key words: water-retention capacity; capillary pressure; hysteresis loop; scanning curves; "pump effect"

Ключевые слова: водоудерживающая способность почвы; капиллярное давление; петля гистерезиса; сканирующие ветви; эффект помпы

Abstract. Designing of underground constructions, such as irrigation and drainage systems, requires engineering surveys. Such surveys include the study of the hydrological conditions of the territory, which are determined by the hydrophysical properties of soils, such as their water-retention capacity. The formation of a hysteresis loop for the soil water-retention capacity occurs because of the variability of meteorological conditions. It is almost impossible to measure all possible scanning branches that fill the gap between the main branches of the hysteresis loop. A mathematical model of the hysteretic soil water-retention capacity is proposed. The model is based on physical concepts of the structure and

Терлеев В.В., Никоноров А.О., Гиневский Р.С., Лазарев В.А., Того И., Топаж А.Г., Моисеев К.Г., Павлова В.А., Лайшев К.А., Архипов М.В., Мельничук А.Ю., Дунаева Е.А., Миршель В. Гистерезис водоудерживающей способности почвы // Инженерно-строительный журнал. 2018. № 1(77). С. 141–148.

capillary properties of the soil pore space. Model parameters are identified by dot fitting using data on the main (boundary) hysteresis branches. Scanning branches starting with pre-calculated reversal points are evaluated. Suggested model has a quite low error to predict the scanning branches of soil water-retention capacity. The use of this model ensures reliable estimates of the hydrological conditions of the territory for underground construction. Also it gives precision irrigation rates which result in reduction of gravitational runoff of excessive moisture, preventing pollution of groundwater with agrochemicals.

Аннотация. Проектирование объектов подземного строительства, таких как ирригационные и дренажные системы, требуют проведения инженерных изысканий. Такие изыскания включают в себя изучение гидрологических условий территории, которые определяются гидрофизическими свойствами почв, например, их водоудерживающей способностью. Изменчивостью метеорологических условий обусловлено формирование петли гистерезиса водоудерживающей способности почвы. Измерение всех возможных сканирующих ветвей, заполняющих промежуток между главными ветвями петли гистерезиса, практически невозможно. Предложена математическая модель гистерезиса водоудерживающей способности почвы. Модель основана на физических представлениях о строении и капиллярных свойствах пространства почвенных пор. Параметры модели идентифицируются путем точечной аппроксимации с использованием данных о главных (граничных) ветвях гистерезиса. Оценены сканирующие ветви, начинающиеся с предварительно рассчитанных поворотных точек. Наряду с обеспечением достоверных оценок гидрологических условий территории подземного строительства, использование данной модели позволяет более точно рассчитать нормы орошения сельскохозяйственных культур. Применение прецизионных норм орошения предотвращает гравитационный сток избыточной влаги, существенно уменьшает вымывание удобрений, мелиорантов и средств защиты растений за пределы корнеобитаемого слоя почвы и, как следствие, снижает риск загрязнения грунтовых вод агрохимикатами, что имеет важное эколого-экономическое значение.

1. Introduction

To substantiate acceptance of the engineering solutions for the construction and operation of hydraulic structures (including urban underground infrastructure objects, irrigation and drainage systems of agriculture), data on the hydrological conditions of the territory are very important. These conditions are largely determined by the hydrophysical properties of the soil. Among these properties is the water-retention capacity of the soil. This property is usually described as a dependence of the volumetric soil water content θ [$cm^3 \cdot cm^{-3}$] on the capillary pressure (potential) of the soil moisture ψ [cm H_2O] [1–4].

Direct measurement of the $\theta(\psi)$ dependence is a rather laborious process [5]. Because of the hysteresis, the water-retention capacity of the soil is characterized by a multitude of branches of this dependence. However, usually only the main (boundary) branches of the hysteresis loop are to be measured [6]. The scanning branches that fill the hysteresis loop are measured much less frequently. Limited number of scanning branches is chosen arbitrary. Measuring the entire range of scanning branches is rather problematic. Nevertheless, during the periods of projecting and constructing activities and also under the actual conditions of operation of the irrigation and drainage systems these data can be necessary for the justification of the engineering solution. But it is not possible to predict what exact scanning branch will be required. Thus, we face the problem of estimating of the scanning branches from using the available data, for example, data on the main (boundary) branches of the hysteresis loop. The only rational way to solve this problem is the method of mathematical modeling.

Several mathematical models had been suggested before [7–14]. The authors of this paper investigated the mathematical model based on physical concepts of the structure and capillary properties of soil pores [15–19]. This model allows estimating the scanning branches of the hysteretic soil water-retention capacity. Description of the model is given in part 2 Method.

The purpose of the work is the verification of the investigated model [15–18]. Verification of this model is based on literature data on four soils: White silica sand [12], Dune sand [19], Rideau clayey loam and Rubicon sandy loam [20]. The tasks of the study are comparison the investigated model with three analogical models [12–14]. The results of the work could be applied in the various hydraulic engineering projects [21].

2. Method

Numerical methods and computational experiments are used to solve the problems posed in this study. To describe the mathematical model, an analytical method is used. The water-retention capacity of the soil is described by formula:

$$S_e = \begin{cases} \frac{1}{2}\operatorname{erfc}\left(\frac{n\sqrt{\pi}}{4}\ln\left(\frac{\psi-\psi_{ae}}{\psi_0-\psi_{ae}}\right)\right) \approx \left(1+\left(\frac{\psi-\psi_{ae}}{\psi_0-\psi_{ae}}\right)^n\right)^{-1}, & \psi < \psi_{ae}; \\ 1, \ \psi \geq \psi_{ae}, \end{cases} \tag{1}$$

where: $S_e = (\theta-\theta_R)/(\theta_S-\theta_R)$ − effective soil saturation with moisture; θ_S [cm^3·cm^{-3}] – maximum volumetric soil water content; θ_R [cm^3·cm^{-3}] – minimum volumetric soil water content at which the moisture has the properties of a liquid; ψ_{ae} [cm H_2O] – capillary pressure of soil moisture at air entrance (bubbling pressure); ψ_0 [cm H_2O] – capillary pressure, which corresponds to the most probable value of the random variable − the logarithm of the effective radius of the soil pore; σ − standard deviation of this random variable; $n = 4/(\sigma\sqrt{2\pi})$; $\operatorname{erfc}(z) = 1-(2/\sqrt{\pi})\int_0^z \exp(-t^2)dt$ − complementary error function.

To describe the hysteretic soil water-retention capacity, formula (1) is applied with two sets of parameters: $\psi_{0,w}$ [cm H_2O], ψ_{we} [cm H_2O] and n_w (for wetting), as well $\psi_{0,d}$ [cm H_2O], ψ_{ae} [cm H_2O] and n_d (for drying). Scanning (primary, secondary, etc.) branches start from turning points. The algorithm for calculating the reversal points is proposed in the literature [13]. Formula (1) with relations for the reversal points describe the mathematical model of the hysteretic soil water-retention capacity [15-18] investigated here.

3. Results and Discussion

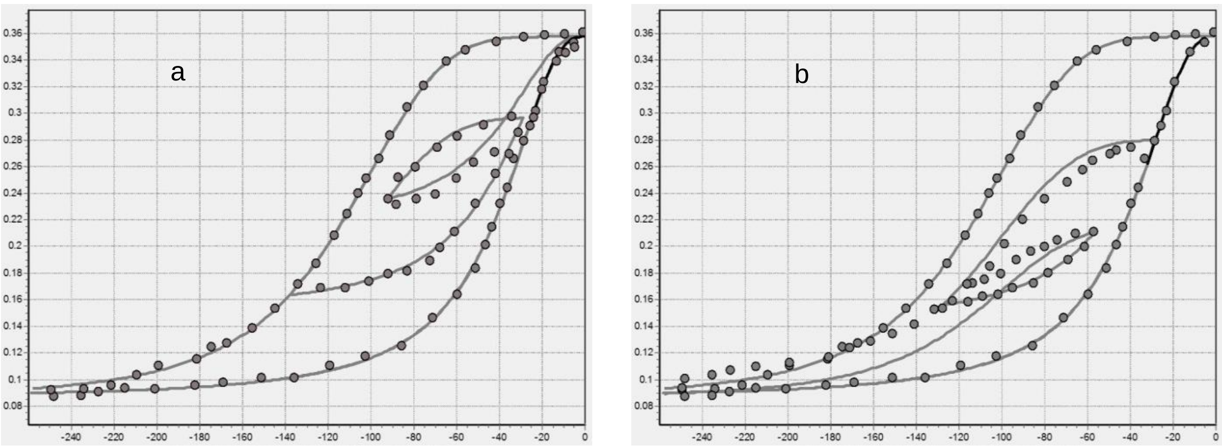
The model (1) parameters were identified from the measured data on the main (boundary) branches of the hysteresis. Then, using the identified parameters, the scanning branches were calculated. Based on a comparison of such calculated scanning branches with experimental data that were not used to identify the parameters, it is possible to characterize the predictive accuracy of the model with respect to the estimated hysteresis scanning branches. Using the formula (1), the following computational experiments were performed: 1) identification of the parameters of the model investigated here by dot approximation (fitting) procedure of data on the main (boundary) branches (Table 1, Table 2); 2) predictive estimation of hysteresis scanning branches.

Table 1. The parameters of the model investigated here, which have been identified from data on the main (boundary) branches of the hysteretic soil water-retention capacity by means of a dot approximation (fitting) procedure

Soils	**Parameters**							
	θ_R	θ_S	ψ_{ae}	ψ_{we}	$\psi_{0,d}$	$\psi_{0,w}$	n_d	n_w
White silica sand	0.0861	0.3574	−12.09	−1.797	−112.2	−41.42	3.996	2.287
Dune sand	0.0934	0.3010	−19.82	−3.594	−33.68	−19.99	3.170	3.298
Rideau clayey loam	0.2896	0.4179	−20.00	6.26	−66.96	−29.44	1.951	1.999
Rubicon sandy loam	0.1688	0.3829	−13.00	16.00	−88.42	−36.32	2.911	2.993

On Figures 1a,b–4a,b the measured data are shown by dots; the results of the dot approximation (fitting) procedure for the main (boundary) branches, as well as the results of the predictive estimation for the scanning branches of hysteresis loop (using the model investigated here) are shown by solid curves. Based on the computational experiments, a comparative analysis for an accuracy of the predictive estimating the hysteresis scanning branches was carried out. The model investigated here and three analogical models [12–14] were used.

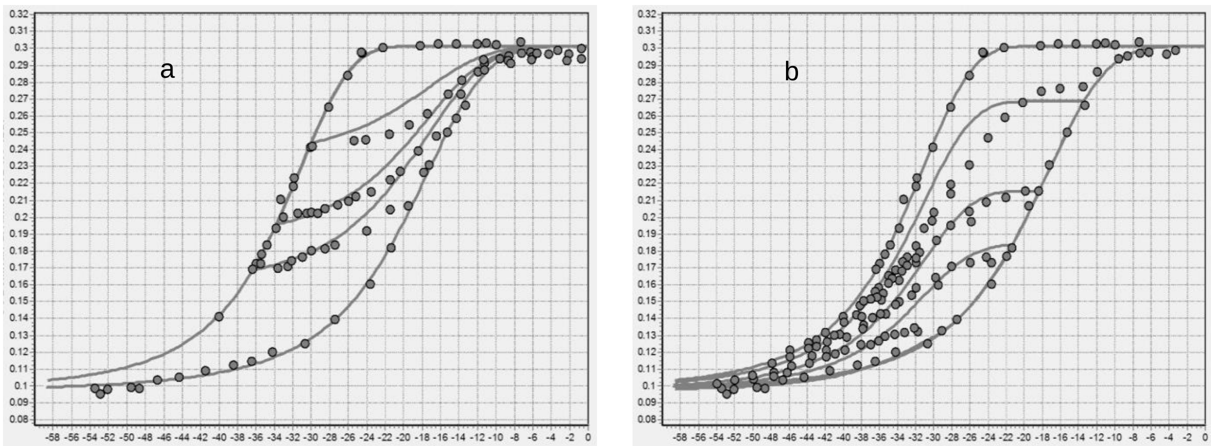
In Table 2 and Table 3 the underlined font indicates the minimum average absolute values of the deviation of the results for the dot approximation (fitting) procedure, as well as for predictive estimating the hysteresis scanning branches, from the corresponding measured data. From Table 2 and Table 3 it is clear that the model presented in this paper most often shows the best result for dot approximating (fitting) the measured data on the main (boundary) branches, and also this model most often achieves the highest accuracy for the predictive estimates of the scanning branches of the hysteresis loop. The quite low mean absolute values of the deviation between the simulation results and the experimental data confirm that the model investigated here corresponds to physical concepts of the nature of the soil hysteretic water-retention capacity.



Volumetric water content [cm^3·cm^{-3}]

Capillary pressure (capillary-sorption potential) of soil moisture [cm H_2O]

Figure 1. White silica sand. Using the investigated model for dot approximation (fitting) of measured data on the main branches and for predictive estimation of:
a) the wetting primary branch, the drying secondary branch, the wetting tertiary branch;
b) the drying primary branch, the wetting secondary branch, the drying tertiary branch



Volumetric water content [cm^3·cm^{-3}]

Capillary pressure (capillary-sorption potential) of soil moisture [cm H_2O]

Figure 2. Dune sand. Using the investigated model for dot approximation (fitting) of measured data on the main branches and for predictive estimation of:
a) the three wetting scanning branches; b) the four drying scanning branches

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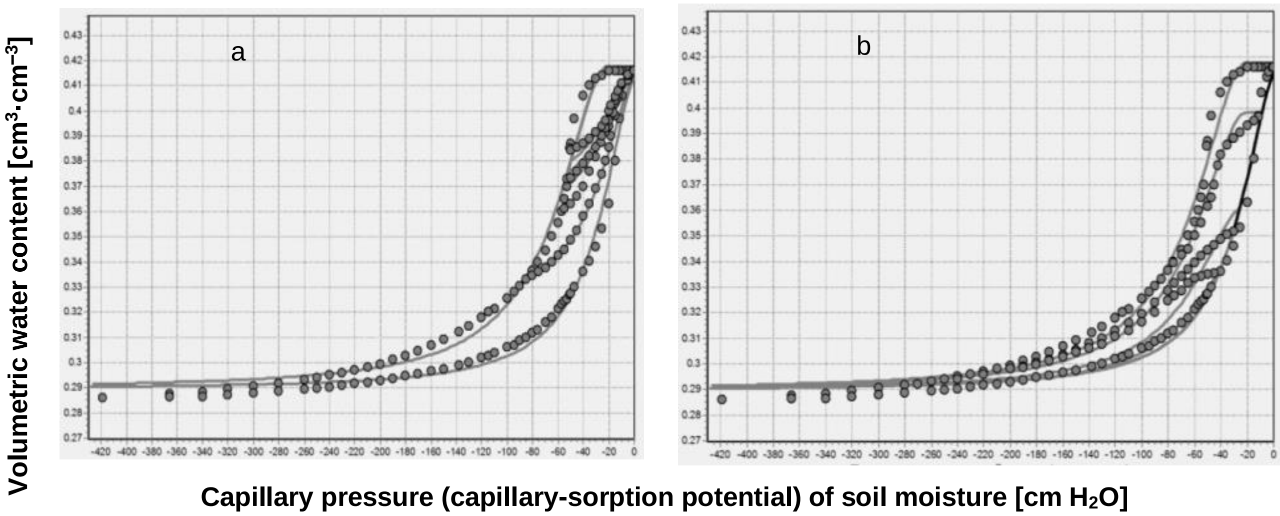

Figure 3. Rideau clayey loam. Using the investigated model for dot approximation (fitting) of measured data on the main branches and for predictive estimation of:
a) the four wetting scanning branches; b) the three drying scanning branches

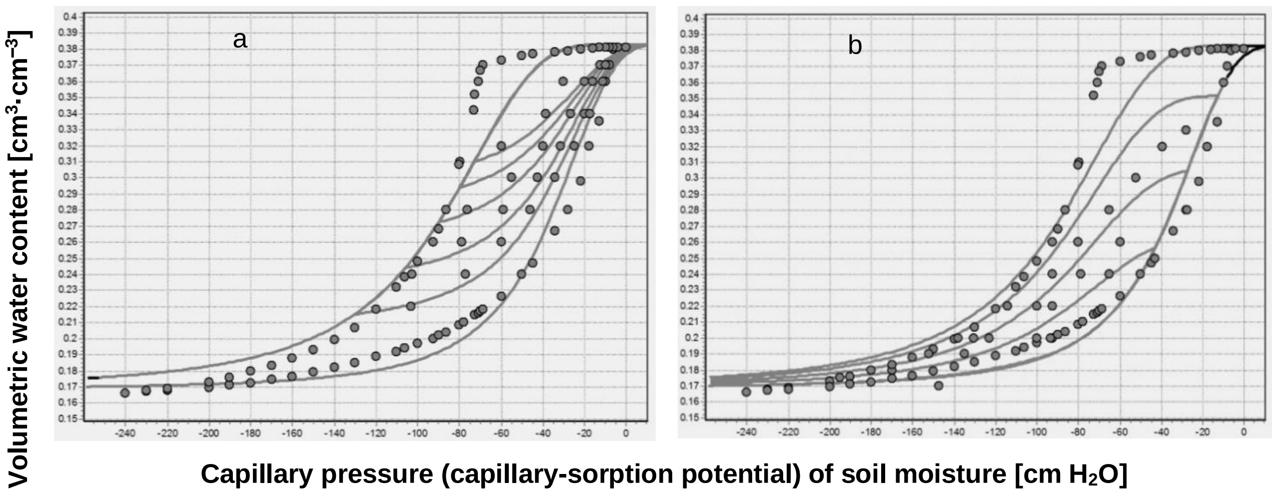

Figure 4. Rubicon sandy loam. Using the investigated model for dot approximation (fitting) of measured data on the main branches and for predictive estimation of:
a) the five wetting scanning branches; b) the four drying scanning branches

It should be noted that the investigated model, in principle, does not exclude the possibility of undesirable artificial "pump effect", as well as the intersection of the main and scanning hysteresis branches. This effect consists in the fact that with the oscillation of the capillary pressure of the moisture in a fixed range of values, the volume water content can assume values that go beyond physically acceptable frames. Such possibility is due to the formal character of the mathematical description. Indeed, for an arbitrary choice of parameter values, a "pump effect" cannot be ruled out. At the same time, if the values of the parameters are physically realistic (reliable), then the "pump effect" cannot arise. Of course, the property of physical adequacy (realistic and reliability) of parameter values is inherent only in those parameters that have a physical sense [13]. Otherwise, the absence of a "pump effect" cannot be guaranteed [14]. Models with artificially closed loops formed by the main and scanning hysteresis branches, in the opinion of the authors of this work, are physically absurd and untenable, since in this case at the reversal points the function of the soil differential moisture capacity assumes an unlimited number of values [12]. More realistic is the assumption that this function takes only two values (one for drying and one for wetting). As a rule, the formal (that have no physical interpretation) models are characterized by low accuracy of predictive estimates. Only a physically adequate model, coupled with realistic and reliable values of the interpreted parameters, excludes the appearance of undesirable artificial "pump effect", and also allows accurate prediction of the scanning hysteresis branches. The model investigated in this work refers to the type of physically adequate models [15–18]. The use of

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precision irrigation rates calculated with the help of the model investigated and verified by the authors prevents the excess moisture from draining and thus minimizes the loss of irrigation water, as well as the unproductive losses of fertilizers, ameliorants and plant protection matters due to the leaching of agrochemicals beyond the root layer of the soil.

Table 2. The average absolute deviation between the measured data cited from the literature and main (boundary) branches calculated using the four models by means of a dot approximation (fitting) procedure

Soils	**Models**			
	Scott et al.	Kool and Parker	Huang et al.	Investigated
White silica sand	0.0028	0.0107	0.0030	0.0019
Dune sand	0.0027	0.0080	0.0031	0.0023
Rideau clayey loam	0.0032	0.0057	0.0057	0.0032
Rubicon sandy loam	0.0045	0.0130	0.0055	0.0098

Table 3. The average absolute deviation between the measured data cited from the literature and hysteretic scanning branches estimated using the four models

Soils	**Scanning branches**	**Models**							
		Scott et al.		Kool and Parker		Huang et al.		Investigated	
		Wetting	Drying	Wetting	Drying	Wetting	Drying	Wetting	Drying
White silica sand	Primary	0.0033	0.0070	0.0035	0.0028	0.0035	0.0066	0.0024	0.0087
	Secondary	0.0029	0.0035	0.0054	0.0095	0.0050	0.0031	0.0014	0.0028
	Tertiary	0.0099	0.0128	0.0130	0.0137	0.0082	0.0042	0.0130	0.0149
Dune sand	Primary	0.0074	0.0096	0.0096	0.0151	0.0057	0.0096	0.0067	0.0095
Rideau clayey loam	Primary	0.0038	0.0050	0.0024	0.0065	0.0034	0.0071	0.0024	0.0062
Rubicon sandy loam	Primary	0.0106	0.0141	0.0118	0.0175	0.0076	0.0105	0.0052	0.0108

4. Conclusions

The importance of the study is that the using the mathematical model of the hysteretic soil water-retention capacity presented here provides an opportunity to assess the soil hydrophysical characteristics that are applied in the design of hydro-technical structures, as well as in the calculation of irrigation rates. The estimates obtained in the framework of computational experiments with this model contribute to an increase in the study effectiveness of the hydrological conditions of the hydraulic structures territory when performing pre-project engineering surveys. The model investigated in the work is verified. The verification was based on literature data on four soils: *White silica sand, Dune sand, Rideau clayey loam* and *Rubicon sandy loam*. Comparisons of the investigated model were carried out with respect to three analogical models. It is shown that the model investigated in this work has the highest accuracy for estimating the scanning hysteresis branches of the studied soils. The results of the research can be applied at designing various facilities of hydraulic engineering and underground construction as well at developing a precision irrigation technology.

5. Acknowledgments

The work is supported by DAAD (PID: 91619700; A/10/01103), RFBR (No. 16-04-01473-a).

Terleev V.V., Nikonorov A.O., Ginevsky R.S., Lazarev V.A., Togo I., Topaj A.G., Moiseev K.G., Pavlova V.A., Layshev K.A., Arkhipov M.V., Melnichuk A.Yu., Dunaieva I.A., Mirschel W. Hysteresis of the soil water-retention capacity: estimating the scanning branches. *Magazine of Civil Engineering*. 2018. No. 1. Pp. 141–148. doi: 10.18720/MCE.77.13.

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