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Hysteretic water-retention capacity of sandy soil

Гистерезис водоудерживающей способности почвы на примере песчаных почв

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Key words: soil; water-retention capacity; hysteresis; reversal points; scanning curves; approximation accuracy; “pump effect”, parameters identifying; model verification

Ключевые слова: почва; водоудерживающая способность почвы; гистерезис; поворотные точки; сканирующие кривые; точность аппроксимации; эффект «помпы»; идентификация параметров; верификация модели

Abstract. Before the construction project, it is necessary to investigate the hydrological conditions of territory. For this purpose some hydrophysical indicators of the soil should be measured. Among the most important indicators is the water-retention capacity. It is convenient to use a physically justified model to research sorption-desorption properties of soil with respect to moisture. The authors have investigated the mathematical model, which was developed to describe the hysteresis of water-retention capacity. The computer program “HYSTERESIS” was been used to implement this research. Three computational experiments were carried out with the use of this program. The results allow improving the accuracy of calculating the dynamics of soil moisture. The results of the research could be applied to the agricultural research, hydrological conditions investigations and other area of knowledge.

Аннотация. Перед началом проектирования строительства необходимо исследовать гидрологические условия территории. Для этого необходимо измерить некоторые гидрофизические показатели почвы. Среди наиболее важных показателей – водоудерживающая способность. Целесообразно использовать физически-обоснованную модель для исследования сорбционно-десорбционных свойств почвы по отношению к влаге. Авторы исследовали математическую модель, которая была разработана для описания гистерезиса водоудерживающей способности. Для реализации этого исследования была использована компьютерная программа «HYSTERESIS». С помощью этой программы было проведено три вычислительных эксперимента. Полученные результаты позволяют повысить точность расчета

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динамики влажности почвы. Результаты исследования могут быть применены к сельскохозяйственным исследованиям, исследованиям гидрологических условий.

Introduction

There is a need for different soil properties modelling, such as water-retention capacity, for various engineering purposes, especially in urban environmental engineering. Water-retention capacity (WRC) of soil is described by a functional dependence of volumetric water content θ ($cm^3 \cdot cm^{-3}$) on capillary pressure (capillary-sorption potential) of moisture ψ (cm H_2O). There are number of problems for the WRC models, such as:

- accounting the hysteresis phenomena during the physical justification and mathematical formulation of the WRC function;
- difficulties during the construction of scanning curves of hysteretic WRC loop, starting from reversal points.

Taking into account the hysteresis phenomena, some extension of the approach proposed by Kosugi [1–4] is developed [5–8]. There the WRC function and its approximation are suggested. This function describes a main drying curve (MDC), a main wetting curve (MWC) and also scanning curves of the hysteretic WRC [5–8].

The purposes of the work are: 1) evaluation of accuracy approximation to WRC function on examples of MDC and MWC; 2) proof on the absence of "pump effect" for hysteretic WRC model; 3) verification of this model using the measured data on sandy soil.

Method

Considering the soil as a capillary-porous media, the physical and statistical description for the hysteresis of water-retention capacity is offered. It is represented in the form of relations:

$$\theta = \begin{cases} \theta_r + ((\theta_s - \theta_r)/2)\operatorname{erfc}\left(\left(n_d\sqrt{\pi}/4\right)\ln\left(-\alpha_d(\psi - \psi_{ae})\right)\right), \psi < \psi_{ae}; \\ \theta_s, \psi \geq \psi_{ae}; \end{cases} \quad (1a)$$

$$\theta \approx \begin{cases} \theta_r + (\theta_s - \theta_r)/\left(1 + \left(-\alpha_d(\psi - \psi_{ae})\right)^{n_d}\right), \psi < \psi_{ae}; \\ \theta_s, \psi \geq \psi_{ae}; \end{cases} \quad (1b)$$

$$\theta = \begin{cases} \theta_r + ((\theta_s - \theta_r)/2)\operatorname{erfc}\left(\left(n_w\sqrt{\pi}/4\right)\ln\left(-\alpha_w(\psi - \psi_{we})\right)\right), \psi < \psi_{we}; \\ \theta_s, \psi \geq \psi_{we}; \end{cases} \quad (2a)$$

$$\theta \approx \begin{cases} \theta_r + (\theta_s - \theta_r)/\left(1 + \left(-\alpha_w(\psi - \psi_{we})\right)^{n_w}\right), \psi < \psi_{we}; \\ \theta_s, \psi \geq \psi_{we}, \end{cases} \quad (2b)$$

where ψ_{ae} – capillary pressure of moisture, is interpreted as a "pressure of air entrance" on drainage isotherm (cm H_2O), $\psi_{ae} \leq 0$;

ψ_{we} – capillary pressure of moisture, is interpreted as a "pressure of water entrance" on the moistening isotherm (cm H_2O), $\psi_{we} \geq \psi_{ae}$;

θ_s – saturated volumetric water content ($cm^3 \cdot cm^{-3}$);

θ_r – minimum specific volume of liquid water in the soil ($cm^3 \cdot cm^{-3}$);

α_d (cm H_2O^{-1}), n_d, α_w (cm H_2O^{-1}), n_w - appropriate to drainage and moistening physically interpreted parameters.

These parameters can be estimated by the formulae:

$$\alpha_d = r_{0,d}/\beta,\ n_d = 4/\left(\sigma_d\sqrt{2\pi}\right),\ \alpha_w = r_{0,w}/\beta \text{ and } n_w = 4/\left(\sigma_w\sqrt{2\pi}\right),$$

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where $r_{0,d}$ and $r_{0,w}$ - appropriate to drainage and moistening values of the effective soil pore radii, which correspond to the most probable values of the normally distributed random variable - the natural logarithm of effective soil pore radii;

σ_d and σ_w - appropriate to drainage and moistening values of random variable standard deviation - the natural logarithm of effective soil pore radii;

$\beta = 2\gamma\cos\varphi/(g\rho_w)$ (where: γ - surface tension of water at the interface with air; ρ_w - water density; φ - contact angle of the surface of soil particles with water; g - gravity acceleration); it is estimated as follows: β = 0.149·10-4 m^2 [3, 4, 9, 10].

The relations (1a) и (2a) respectively describe MDC and MWC of the hysteretic WRC loop. The relations (1b) и (2b) respectively describe approximations to MDC and MWC in the class of elementary functions. Further, these approximations are recognized to describe the scanning curves of hysteretic WRC.

The drying scanning curves, starting from the reversal point (which is characterized by ψ_i and θ_i the values), are described by the system of relations:

$$\begin{cases} \left[\begin{array}{l} \theta = \theta_r + \left(\theta_s^* - \theta_r\right)\Big/\left(1 + \left(-\alpha_d\left(\psi - \psi_{ae}\right)\right)^{n_d}\right), \\ \theta_s^* = \theta_s,\ \psi_{ae} < \psi_{we} \le \psi_i,\ \psi < \psi_{ae}; \\ \theta_s^* = \theta_i,\ \psi_{ae} \le \psi_i \le \psi_{we},\ \psi < \psi_{ae}; \\ \theta_s^* = \theta_i + \left(\theta_i - \theta_r\right)\left(-\alpha_d\left(\psi_i - \psi_{ae}\right)\right)^{n_d},\ \psi_i < \psi_{ae} \le \psi_{we},\ \psi \le \psi_i; \end{array}\right. \\ \left[\begin{array}{l} \theta = \theta_s,\ \psi_{ae} < \psi_{we} \le \psi_i,\ \psi_{ae} \le \psi \le \psi_i; \\ \theta = \theta_i,\ \psi_{ae} \le \psi_i \le \psi_{we},\ \psi_{ae} \le \psi \le \psi_i. \end{array}\right. \end{cases} \tag{3a}$$

The wetting scanning curves, starting from the reversal point (which is characterized by ψ_j and θ_j values), are described by the system of relations:

$$\begin{cases} \left[\begin{array}{l} \theta = \theta_r^* + \left(\theta_s - \theta_r^*\right)\Big/\left(1 + \left(-\alpha_w\left(\psi - \psi_{we}\right)\right)^{n_w}\right), \\ \theta_r^* = \theta_j = \theta_r,\ \psi_j << \psi_{ae},\ \psi_j \le \psi < \psi_{we}; \\ \theta_r^* = \theta_j - \left(\theta_s - \theta_j\right)\left(-\alpha_w\left(\psi_j - \psi_{we}\right)\right)^{-n_w},\ \psi_j < \psi_{ae},\ \psi_j \le \psi < \psi_{we}; \end{array}\right. \\ \left[\begin{array}{l} \theta = \theta_s,\ \psi_j < \psi_{ae},\ \psi_{we} \le \psi; \\ \theta = \theta_j = \theta_s,\ \psi_{ae} \le \psi_j,\ \psi_j \le \psi. \end{array}\right. \end{cases} \tag{3b}$$

Results and Discussion

Approximation. On the base of hysteretic WRC model, which was described by relations (3a) and (3b), a computer program “HYSTERESIS” is developed [5]. This program was used to carry out some computational experiments with the hysteretic WRC model. The scenario for variation of the capillary pressure of soil moisture was formed before the start of the experiment in a specific text file with the data source (*.exd). By means of the program “HYSTERESIS” and applying the Levenberg-Marquardt algorithm [11, 12], the hydrophysical parameters for MDC and MWC have been identified. For this purpose it were used the measured WRC data on sandy soil [13].

Then computer program “HYSTERESIS” was used to calculate the θ values for every measured ψ value on MDC and MWC (Fig. 1).

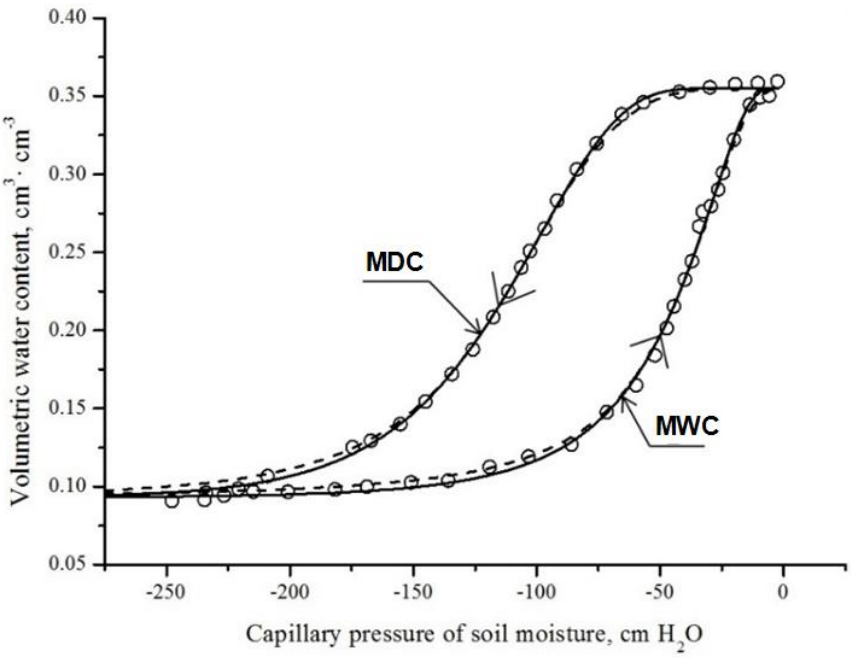

Figure 1. The main hysteretic WRC loop

On the Figure 1 solid lines correspond to the WRC function, describing be relations (1a) and (2a) respectively; dashed lines correspond to approximation for WRC function; circles – measured data. The correlation coefficient between calculated θ values and measured data on MDC and MWC is $R = 0.999$.

Absence of “pump effect”.The internal WRC loops do not go beyond the main drying and wetting curves and approach the previous loops in the process of capillary moisture pressure oscillation (Fig. 2). Therefore, “pump effect” is not manifested in this model.

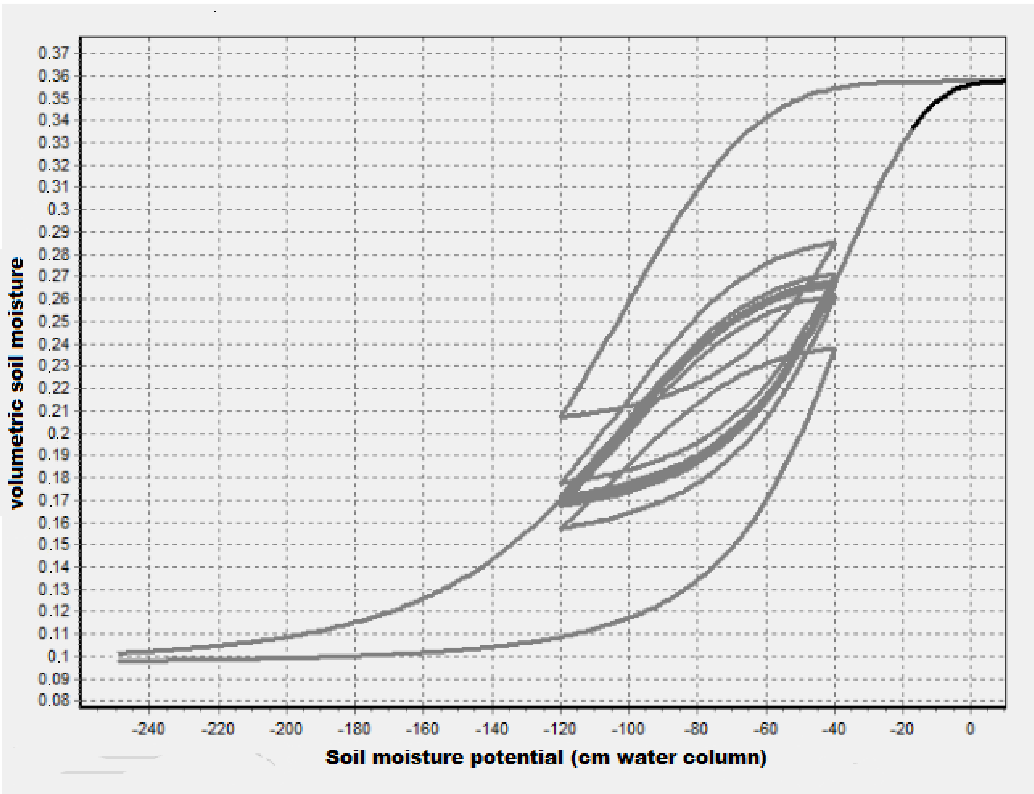

Figure 2. The sequence of the WRC hysteresis loop
under the oscillation of the capillary pressure of soil moisture

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Verification of WRC model.Using the parameters (identified according to the measured data on MDC and MWC), the θ values for primary drying curve (PDC) and secondary wetting curve (SWC) of the hysteretic WRC have been predicted. Among the parameters of the program the value bubbling pressure ψ_{ae} on MDC had been previously zeroed, because this value (based on the physical representations) cannot be positive, and the corresponding experimental data are not available. The predicted θ values are compared with the measured WRC data. On Figure 3 black dots connected by a continuous curve shows MDC, MWC, PDC and SWC of the hysteresis loop: ψ values plotted on the horizontal axis, θ values - on the vertical axis; red dots shows the measured WRC data. According to the theoretical (predicted) and experimental (measured) ordinates (θ values) for PDC and SWC of WRC hysteresis loop the correlation coefficient $R = 0.995$ was calculated. This coefficient suggests about the high predictive (extrapolating) accuracy of investigated hysteretic WRC model for sandy soils.

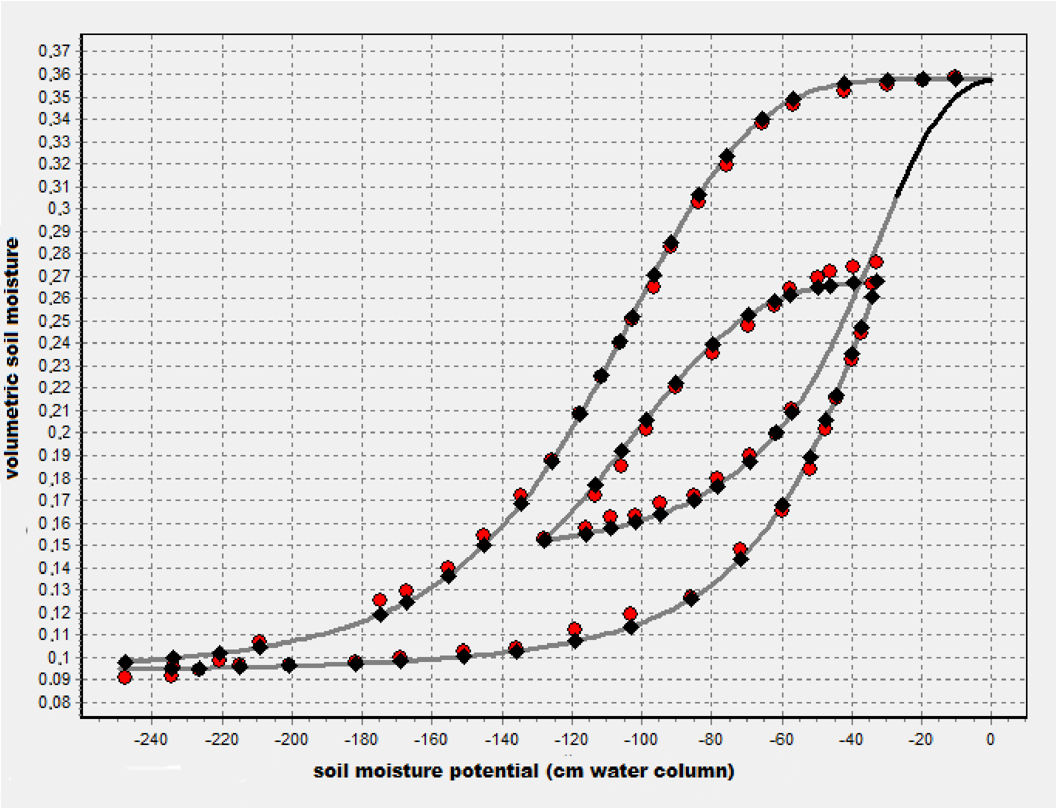

Figure 3. Predicting the internal WRC hysteretic loop formed by the primary drying and secondary wetting curves

On Figure 4 the comparison of the predicted values of volumetric water content with the measured data is represented: here black dots on 1:1 line shows the high convergence of the simulation results and data of the direct measurements (the measured data [13–17] are on the horizontal axis; the computational results are on the vertical axis).

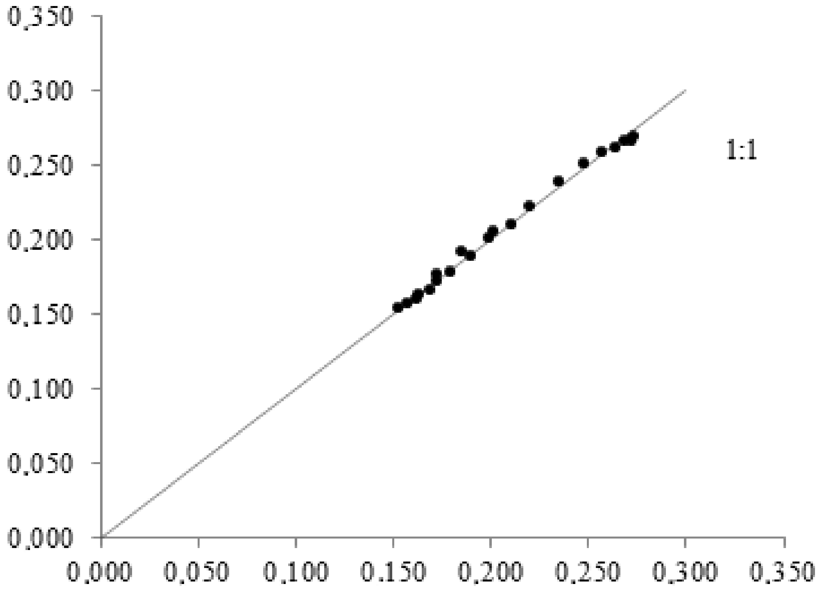

Figure 4. Comparison of the predicted values of volumetric water content with the measured data

Estimates of the scanning curves of the hysteresis loop are important to improve the accuracy of calculating the dynamics of soil moisture [18, 19]. The results of these calculations are used to forecasting the crop yield [20–24], to study the hydrological conditions of the area in the design of irrigation and drainage systems, underground constructions and artificial foundation based on weak soils. In addition, evaluation of the scanning curves are of great importance in the calculating the precision irrigation rates [5] to reduce the wastage of irrigation water, to prevent the removal of agricultural chemicals beyond the root layer of soil and subsequent eutrophication of water bodies, as well as to provide rational use of water resources in general. Soil-hydrophysical investigations and hydrological calculations are also significant for the bank protection tasks [25–27], drainage problems [28, 29], marine works [30, 31], hydropower protection [32], urban ecological, environmental and economical challenges [33, 34]; it helps to find the effective engineering solution based on knowledge of the hydrophysical properties of soils. All these factors indicate the encouraging prospects for the practical use of the proposed WRC model.

Conclusion

Thus, 1) two systems of relations (1a,b) and (2a,b) are received for calculating the main drying and wetting curves of hysteretic WRC; 2) two systems of relations (3a) and (3b) are offered for predicting the scanning drying and wetting curves as well as for calculating the reversal points of hysteretic loop of water-retention capacity. The approximations (1b) and (2b) have quite high accuracy to describe the main drying and wetting curves of hysteretic WRC.

Computer program “HYSTERESIS” was developed on the basis of the proposed model, which is formulated ratios (1b), (2b) and (3a, b). The program allows identifying the model parameters according to direct measurements of the water-retention capacity of soil. Three computational experiments were carried out with the use of this program. The measured data on the water-retention capacity of sandy soil were used in the previous experiments.

The first experiment consisted of comparing the interpolation accuracy using relations (1a) and (2a), on the one hand, and the ratios (1b) and (2b), on the other hand. The result of this experiment shows the high accuracy of the proposed approximations for the function of the water-retention capacity of soil. The second experiment with oscillating values of capillary pressure showed no negative "pump effect". The third experiment was to identify the parameters of the WRC model using data on the main drying and wetting curves and then - in the subsequent prediction of the primary drying curve and secondary wetting curve of hysteresis loop. The result of the third experiment showed high accuracy for extrapolation (prediction) of volumetric water content values for the scanning curves of the hysteresis loop in the absence of data on these curves. This result is explained by the fact that adequate physical representation about the nature of the phenomenon of hysteretic water-retention capacity is the basis for the offered model. The practical significance of the proposed model is the availability of the option in the program "HYSTERESIS" for predicting the scanning curves using the data about the main drying and wetting curves of the hysteresis loop. The particular importance of this option is that the measurement of the totality of the scanning curves practically impossible, while the data on the main drying and wetting curves are relatively accessible.

Estimation of the scanning curves of the hysteresis loop allows improving the accuracy of calculating the dynamics of soil moisture. The results of the research could be applied to the agricultural investigations, hydrological conditions measurements and other measures. All these factors indicate the encouraging prospects for the practical use of the proposed WRC model.

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