Hydrophysical aspects of soil assessment in melioration

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Abstract. Efficient planning of the improvement of soil hydrophysical properties in reclamation requires a prior assessment of soil quality to determine weak points and the vector of complex impacts on soil. The water retention curve and the function of moisture conductivity have a decisive impact on moisture movement in the soil. However, neither WRC nor the function of hydraulic conductivity alone gives a full picture showing moisture supply of plants. Therefore, the function, which is their product, is of particular interest for reclamation purposes. The analytical study of this function allows determining the moisture values related to the transitions from one state to another (the plant wilting moisture, the moisture of the “ripeness” of the soil, etc.) on the bases of laws of Physics. Such types of land clearance operations as sanding, claying as well as breaking up and puddling of soil can be assessed quantitatively applying the above function. The analytical foundation of the fact that less puddled soil reaches a certain level of water holding at higher moisture than more puddled soil has been given. Puddled soil either does not reach such a level or reaches it at lower moisture. The considered function allows estimating the results of increasing the specific surface of soils due to the application of ameliorants. The results of tripolite application in black soil and gray forest soil were received.

1. Introduction

To plan changes in soil properties during land clearance operations efficiently and to determine their quantitative parameters, it is necessary to carry out a comparative assessment of soil quality (bonitation). Ball approach used in bonitation enables to “weak” points and the vector of complex measures that increases its potential fertility and productive capacity of the soil most efficiently. Historically, in Russia, regional bonitation methods, correlating yield and taking into account the properties of soil in certain regions have become widespread. This resulted in a wide range of sets of criteria to assess the properties of soil.

A comprehensive analysis of the soil as an agro-ecosystem requires taking into account the fact that fertilizers, ameliorants, type and degree of tillage make a relatively short-term seasonal contribution to the agronomic value of the soil. This short-term seasonal measures contribute to such hydrophysical properties as the volumetric specific surface of soil composing particles and the volumetric specific surface energy of soil moisture that are time-stable. This approach to the problem is due to the fact that the combination of physical and hydrophysical properties of the soil have a decisive effect on the harvest and the moisture movement in the soil. The water retention curve (WRT) and the function of moisture conductivity [1-4], are the most important of them since they determine speed and direction of soil moisture movement, and, consequently, the intensity of moisturizing and drying, that is, the moisture supply to plants.
The soil specific surface is a time-stable property of the soil-forming rock, which determines its capacitive characteristics in relation to water. Porosity is not a time-stable property and its value changes during agronomic amelioration and land clearance operations (plantine plowing; deep tilling, rototilling).

Sandy and sandy loam soils with small values of specific surface (1.5-2 m²/g) have a favorable air and thermal regime. They are not-watertight, but have poor water capacity. Clay soils with much higher specific surface (300-400 m²/g) have high water capacity, poor water return poor, thermal properties and they are not-watertight enough. Loams which have intermediate values of specific surface and take an intermediate position according to their properties are the best ones.

They have a favorable air and thermal regime, high water capacity and moisture mobility and they are not-watertight enough.

In this respect, the development of theoretical approaches to provide reasons for this soil characteristic, which allows assessing its agronomic value taking into account hydrophysical properties, is an urgent fundamental problem of agricultural science.

At the same time, the application of information technologies, methods of mathematical statistics and developed technical means allows both to determine the soil bonitet rather accurately and quickly and to optimize reclamation measures and technologies.

2. Materials and methods
To estimate the soil condition it is proposed to develop and use a value that takes into account the water retention curve and the function of soil moisture conductivity. This choice is due to the fact that these characteristics are unique for any soil sample and are related to the granulometric, microaggregate, aggregate soil composition, the specific surface of soil particles and they characterize the structure of the soil space. However, even first insight into the problem the problem reveals the fact that a high level of water-holding capacity of the soil and low level of moisture conductivity are interrelated. A good example is clay soils that hold moisture well but conduct it poorly. On the contrary the better the moisture conductivity, the worse the water-holding property; of soils. In this case, we can speak about sandy soils with good moisture conductivity but poor moisture holding.

Thus neither WRC nor a function of moisture conductivity alone gives a full picture that showing the moisture supply of plants. Soil porosity can be considered as the maximum amount of moisture it can hold. At the same time, the soil-water potential is responsible for the soil water holding, and the function of moisture conductivity is responsible for its movement. Therefore, the function, which is their product is of particular interest for the soil development. We use a physical analogy with the phenomenon of heat transfer in thermodynamics. Similar to the way the thermal diffusivity is related to thermal conductivity and specific heat capacity, we introduce moisture conductivity and moisture potential into a new function. The formula for WRC - dependence of the potential $\psi$ on volumetric moisture $w$ can be presented in the form [1]:

$$\psi = \psi' + \psi'' = \frac{\Omega_0^3}{\rho w^3} + \frac{\Omega_0 \sigma f}{\rho} \cdot D(w, \Pi_0),$$  \hspace{1cm} (1)

where $\Omega_0$ is volumetric specific surface, (m³/m³); $w$ - volumetric water content, (m³/m³); $\sigma f$ - specific free surface energy at the water/air boundary J/m²; $\rho$ - water density kg/m³; $A$ - constant, $J$; $D(w, \Pi_0)$ - the function taking into account granulometric composition.

For moisture conductivity we can put the following [2]:

$$K = \frac{\pi^2}{\Omega_0 \eta S^2} \cdot \frac{\lambda \Pi_0^a}{1 - \Pi_0} \left[ 1 - \left( \frac{1 - w}{\Pi_0} \right)^2 \right],$$ \hspace{1cm} (2)

where $\eta$ - water viscosity, Pa c; $S$ - cross-section area of soil sample the water flows through; $\lambda$, $\alpha$ - coefficients.

Since the function given for assessing soil condition is $V(\Pi_0, \Omega_0, w) = K(\Pi_0, \Omega_0, w) \psi(\Pi_0, \Omega_0, w)$ we analyze it for extremum as the moisture function. The diagram of the dependences between the moisture
The properties of soil moisture vary greatly depending on the filling of the pore space. With moisture content increase in the soil, the ratio of forces of different nature acting on water changes and the system goes through a number of different states. The use of the function $V(w)$ and its derivatives allows us to determine the humidity values corresponding to the transition from one state to another. Soil rheological models are commonly used for the same purpose. The wilting moisture of the plants corresponds to the beginning of liquid "cuff" formation and is described by the equation:

$$pF = 2.17 + 15w,$$

(3)

“Ripeness” of the soil is the state corresponding to the maximum molecular moisture capacity reflecting the balance of pressures in the "film" and "cuff" state is described by the equation:

$$pF = 2.17 + 3w,$$

(4)

The point at which gravitational forces begin their manifestation, i.e. the maximum capillary-sorption moisture capacity corresponds to the equation:

$$pF = 2.17 + w,$$

(5)

We can consider the formulae (3-5) to be regression, but at the same time they can be proved from the point of view of Physics. The analysis of dependences (1), (2) and the value of $V(\Pi_0,\Omega_0,w)$, obtained on their basis make it possible to estimate the energy condition of soil moisture more accurately. For example, if we draw a regression line through the point (0; 2.17) and through the values of WRC at the maximum points of the function $V(\Pi_0,\Omega_0,w)$, it will be expressed as $pF=2.17+15.38w$, that actually corresponds to the wilting moisture. Similarly, the moisture values corresponding to the points of initial sticking can replace the equation (3). They correspond to the "ripe" state of the soil. It was found that the critical values of moisture obtained in analyzing the function $V(\Pi_0,\Omega_0,w)$ make it possible to characterize the water-holding force of soils. It is extremely important for estimation of plant water supply regimes, structural and mechanical properties of soil. Therefore the function $V(\Pi_0,\Omega_0,w)$ can be used for reclamative assessment of soil conditions.

Soil evaporation depends on both its properties and external conditions. The factors determining evaporation have not been sufficiently studied and therefore a number of difficulties arise in forecasting. There is no all-purpose method for describing evaporation found in literature. The application of models...
Evaporation rate depends on external conditions such as temperature, wind speed, topography and vegetation in addition to soil properties. Water evaporation depends greatly on the temperature which determines the energy of soil moisture. Analyzing the evaporation, we’ll take into account some extra energy costs because of the fact that with moisture volume decrease in the soil, the value of the surface condensed phase increases. Enlarging the surface is known to require energy, besides

\[ \Delta E = \sigma \Omega_0 \left( \frac{(\Pi_0 - w + \alpha - \alpha \Pi_0 + \omega)}{(1 - \Pi_0 + w)^2} \right) \left( 1 - \frac{w}{\Pi_0} \right)^\alpha \Delta w. \]  

(6)

The evaporation rate depends not only on the type of liquid, but also on the shape of its surface. In porous bodies, such as soils, the surface of the liquid in most pores has a concave shape. This kind of shape prevents evaporation of liquid. It can be explained by the fact that when the liquid evaporates from a concave surface and its volume decreases then its surface area increases. Increasing the surface area requires extra energy costs which are to be obtained while evaporating from a concave surface. The dependence of specific surface of condensed phase on volumetric moisture content \( \Omega_c(w) \), and the interrelation of surface value and energy makes it possible to link the processes of evaporation and soil water potential or WRC.

Some types of land clearance operations are sanding and claying. In the process of development of any types of soil, their development is carried out to improve the mechanical composition and water-air regime of soils. In sandy soils, claying creates a fertile layer (a layer of clay 5-6 cm is formed, and then a layer of loam or sandy loam is put over it). Gradually, the fertile layer increases to 40 cm [5,6].

To improve clay soils we make them looser by sanding (by applying river sand before plowing). Physico-mechanical properties of the resulting mix of sand, clay soil, shift into the range of values typical for loam.

Quantitative calculation of specific surface changes of the two-component “clay – sand” mixture can be performed with the formula:

\[ \Omega = n_1 \Omega_1 + n_2 \Omega_2, \]  

(7)

where \( n_1 \) and \( n_2 \) – are volumetric fractions of the components with specific surfaces \( \Omega_1 \) and \( \Omega_2 \).

The improvement of the soil occurs with its porosity changing. When loosening and puddling the pore space decreases first of all. Calculation of the pore space change can also be performed with the introduced function \( V(\Pi_0, \Omega_0, w) \).

3. Results and discussion

Here is the effect of soil pulverization / puddling on the intensity of soil drying/ moistening. Since the soil tillage increases porosity and decreases the volumetric humidity, soil moisture transfers into the condition with lower moisture conductivity and greater water holding according to the dependence for the function \( V(\Pi_0, \Omega_0, w) \).
Figure 2. Dependence curves $V(w)$ at various porosity.

The dynamics of function $V(\Pi_0, \Omega_0, w)$ change for different values of porosity of gray forest soil ($\Omega=46.2 \cdot 10^6$, m$^2$/m$^3$) is shown in Figure 2. Figure 2 shows that puddling decreases both the value of the maximum and the corresponding value of moisture. Besides, the moisture values corresponding to the flex point are reduced. This proves that less puddled soil reaches a certain level of water holding at higher moisture in comparison with more puddled soil. Puddled soil either does not reach such a level or reaches it at lower moisture.

Thus, studying the function $V(\Pi_0, \Omega_0, w)$ we obtained an analytical foundation for the fact that the denser soil evaporates moisture faster. This conclusion proves mathematically the experimental data that the water-holding properties of soils are getting worse during puddling.

The considered function $V(\Pi_0, \Omega_0, w)$ made it possible to estimate the results of increasing the specific surface of soils due to the application of ameliorants. The results were obtained on the basis of experimental data on physical characteristics of tripolite of the Shumsky open-cast (Chuvash Republic, Russia): volume mass $\rho=(1.16\div1.97) \cdot 10^3$ kg/m$^3$; density of the solid phase $\rho_s=(2.61\div2.81) \cdot 10^3$ kg/m$^3$; porosity of bulk samples $P=(0.58\div0.64)$; specific surface $\Omega=(0.80\div1.10) \cdot 10^3$ m$^2$/m$^3$. The values of the volumetric mass and porosity vary within these limits depending on the size of the fractions and the degree of puddling. To estimate the effect of tripolite application on $V(\Pi_0, \Omega_0, w)$, we calculate it for black soil and light gray forest soil. The results of the parameters of the obtained mixtures are given in Table 1. The mixtures were obtained as a result of the tripolite application into the original soil normally 10 t/ha with soil depth of 20 cm.

| Soil               | Specific surface ($10^4$ m$^2$/m$^3$) | Porosity | Volumetric mass ($10^3$ kg/m$^3$) |
|--------------------|---------------------------------------|----------|----------------------------------|
|                    | before | after | before | after | before | after |
| Leached black soil | 8.03   | 8.11  | 0.61   | 0.60  | 1.10   | 1.10  |
| Light gray forest soil | 4.61   | 5.32  | 0.54   | 0.57  | 1.15   | 1.14  |

4. Conclusion

Summing up the results of the study, it can be stated that the value of $V(\Pi_0, \Omega_0, w)$ makes it possible to assess the condition of the soil, as well as to predict and quantify the results of reclamation. The obtained functional form of dependence $V(\Pi_0, \Omega_0, w)$ allows us to analyze the changes taking place in the soil relative to the total external impact on the soil. Due to the fact that the formulae are obtained taking into account the physical and hydrophysical properties of the soil, it is justified to use them in studying the
technological properties of the soil during agronomical amelioration and land clearance operations. The study of the relation of the obtained expressions for $V(\Pi_0,\Omega_0,w)$ with hydrological constants and rheological soils samples makes it possible to study the soil condition and the moisture supply to plants on the bases of laws of Physics.

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