Obtaining functional dependence of friction coefficient of soil on steel

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Abstract. The development of theoretical approaches to the substantiation of the water-physical properties of soils, which determine the favorable mode of functioning of tillage machines and units, and the improvement of methods for measuring hydrophysical parameters, is an actual problem of agricultural science. The intensification of technological processes in some cases leads to irreversible changes in the soil profile. The results of the research can be substantially expanded by modeling the hydrophysical properties of the soil and studying the water and air regimes of the soils. In accordance with this, an important task is the theoretical justification of the functional dependence of the frictional force in the soil on its specific surface, porosity and moisture for determining the moisture ranges when which meliorative measures are environmentally friendly and least energy intensive. The methodological basis was the fundamental and applied foundations of soil hydrophysics. The study of the modes of operation of the tillage machines (crumbling / speed) on various types of soils allowed one to determine the most effective moisture intervals at which, with an average fuel consumption from 4.1 to 17 l/ha, it is saved from 0.16 to 0.68 l/ha. This allows one to reduce fuel consumption by 5-7 % and to provide the best mechanical effect on the soil. The application of these methods was based on the use of modern software packages for processing the results of experiments conducted in laboratory and field conditions.

1. Introduction
The use of a wide range of fundamental characteristics of the physical properties of soils for scientific substantiation and technological decisions of various meliorative measures related to the cultivation of lands and the regulation of their water regime allows for an increase in the quality of management decisions made and the efficiency of economic activity. The developed methods make it possible to substantiate environmentally friendly meliorative measures and technologies that ensure the creation of a favorable soil water regime. The results of the research were used to evaluate meliorative measures in the territories of Batyrevsky, Kanashsky and Cheboksary districts of the Chuvash Republic [1-4, 14-16].

Addressing the problem of reducing the energy efficiency of agrotechnical operations associated with the impact on deep subsurface horizons (decompaction and recultivation) is an urgent issue since the energy intensity during deep tillage is high. In addition, the intensity of water absorption during irrigation is strongly affected by the presence of the soil layer (plough pan) compacted at a certain
depth. Therefore, the directions of research to solve the problem of reducing the energy efficiency of reclamation agrotechnical operations associated with the impact on deep subsurface horizons (planning, decompression and recultivation) are among the topical.

Whatever irrational material a plow is made of, it must constantly overcome the resistance of the cultivated soil. Moreover, the frictional force arising on the coulter, ploughshare, dump, field board takes place during all the time of “effective” use of the plow and, accordingly, “depreciates” a substantial part of the costs associated with the plowing process. The share of the resistance attributable to the working bodies (share, disc, cutter, etc.) is 50-60% in the total resistance of the plow. Approximately the same percentage of energy spent on plowing is spent on overcoming friction forces. It is well known that the friction force of a soil on a metal depends both on moisture and on the mechanical composition of the soil. Moreover, with an increase in moisture, after a continuous increase, it begins to decline quite quickly. Therefore, it is important to have a theoretically sound and dependent on the mechanical composition of the soil information on the critical soil moisture corresponding to the greatest friction force. With a certain moisture comes the physical ripeness of the soil. This moisture corresponds to the least traction resistance to plowing, as well as soil sticking and wear of the working parts of the plow.

In connection with the above, we believe that the substantiation of soil moisture, at which it is necessary to carry out operations, and the speed of movement of the units can be carried out considering the dependencies of stickiness and friction force on moisture and the specific surface of the soil [5,13,17,18].

The intensity of water absorption during irrigation is strongly influenced by the presence of a compacted soil layer (plough pan) at a certain depth. Therefore, among the topical are the directions of research to solve the problem of reducing energy efficiency of reclamation agrotechnical operations associated with the impact on deep subsurface horizons (planning, decompression and recultivation) since the energy intensity during deep tillage of soils is quite high. To substantiate soil moisture it is necessary to carry out operations, and the speed of movement of the units can be carried out considering the dependencies of stickiness and friction force on moisture, porosity and specific surface of the soil. The friction forces in the soil appear when it slides relative to the body that is in contact with it (external friction), or the particles that make up the soil relative to each other (internal friction) slip.

We carried out studies of the influence of moisture, porosity and specific surface of the soil on the processes of interaction of tools and units with the soil to establish the ranges of moisture at which carrying out meliorative activities is environmentally friendly and least energy intensive. When carrying out meliorative measures, such as milling, deep loosening and deep plowing during the primary soil treatment, from 30 to 50% of energy of machine-tractor units (MTU) is spent on work to overcome friction forces. Therefore, it is important to choose a moisture with which the soil crumbles well, minimally sticking to the processing tools [19, 20]. This will ensure not only a reduction in tractive effort, but also the best soil condition after the ameliorative event.

2. Materials and methods

The frictional force occurs when an active force tends to move one body relatively another under normal pressure. Friction force F is always located in the plane of interaction of bodies and directed in the opposite direction to the active force [6-13, 22, 23]. We determined from the formulas that:

\[ F = fN, \ \phi = \arctan(F/N), \]

where \( f \) is the coefficient of friction; \( N \) is the force of normal pressure; \( \phi \) is the angle of friction.

For fast and easy measurement of the coefficient of friction (rest / motion), you can use the device of Zeligovskiy or the dynamograph (a disk device measuring friction). The degree of interaction of soil particles with the surface of the working bodies of machines is mainly influenced by the ratio of forces in the systems "particle-particle" and "particle-surface." With increasing differences in this, the ratio increases the fixation and particles on the working surface. We determine the force of fixation through the difference between the resulting friction force among the contacting soil particles and the
force of friction on the surface of the working body \( \Delta F = pz(f - k') \). In this case \( p \) is the specific pressure, \( z \) is the number of contacting with the particle surface, \( f \) is the coefficient of friction between soil particles, \( f' \) is the coefficient of soil particles on the surface of the working bodies, and \( k \) is a constant dependent on the number of contacts.

Adhesion between particles of soil, as a rule, exceeds the adhesion of particles to the surface of the working bodies. Therefore, in addition to reducing fuel costs, the selection of operating modes for which agromeliorative and cultural-technical measures (plowing, deep loosening, milling) are most effective, allows increasing the durability of the working bodies. The coefficient of soil friction depends on many factors, the main of which are mechanical composition and humidity.

Changing the ratio of solid, liquid and gaseous phases in the soil leads to a change in the forces acting in the system “soil tillage tool - soil”. It is therefore important to investigate the dependence of the friction coefficient on the moisture content in the soil. An improved soil structure results in less friction. This is explained by the fact that with an increase in porosity, the area of actual soil contact with the surface of a foreign body decreases, i.e. in dense soil, friction is greater than in loose, structured. At low moisture, the soil moisture is of little concern to the body and has almost no effect on the friction force, i.e. dry friction occurs. In addition, at low moisture from 0 to 8 ... 10 % stickiness does not appear, and the soil moisture does not adhere to the metal (section ab), therefore only the influence of \( F \) for which the coefficient of friction does not depend on moisture. With an increase in soil moisture, the forces of molecular attraction between the soil moisture and the body begin to appear more noticeably; there is a phase of external friction sticking. Slip resistance depends on sticking:

\[
R = k_0S + kSN,
\]

where \( k_0 \) is the coefficient of specific adhesion in the absence of normal pressure; \( k \) is the coefficient of specific adhesion caused by normal pressure, cm²; \( S \) is the contact area, cm².

The effect of moisture on the friction coefficient is shown in figure 1.

![Figure 1. Typical view of the f dependence on moisture.](image)

The increase in \( f \) in the \( bc \) segment is explained by the appearance and increase of stickiness and the forces of molecular attraction of soil particles to the metal surface. When \( w \approx 35\% \) (depending on the mechanical composition of the soil), the values of the friction coefficient reach a maximum. With a further increase in moisture (the \( cd \) segment) \( F \) decreases since the stickiness decreases, and, moreover, the soil moisture begins to play the role of lubricant. If \( F \) depends only on the magnitude of the normal pressure and the properties of materials in contact with the surfaces, then \( R \) influences even without external applied pressure and depends on the size of the touch.

For some intervals of soil moisture, \( F \) and \( R \) act together; both values appear at the same time as the general resistance \( F' = F + R \).

If the sum of the forces \( F+R \) is more than the shear strength of the soil, the working bodies stick. When the sum of the sticking and friction forces of the soil on the soil becomes greater than the total resistance of adhered particles to icing, self-cleaning is observed.
It is well known that the next factor after moisture, which has a significant effect on \( f \), is the mechanical composition of the soil, or rather the particle content is less than 0.1 mm, i.e. physical clay. The smaller the size of the elementary particles of the soil, the greater the coefficient of friction. This fact is fully consistent with the proposed approach. Stickiness is directly proportional to the specific surface of the solid phase \( \Omega \). Therefore, we can conclude that the coefficient of friction should be directly proportional to \( \Omega \), i.e. content of physical clay. It is well known that with an increase in the percentage of physical clay, the coefficient of friction increases. Since dry friction occurs at low humidity and tackiness begins to appear with increasing humidity, the function \( f \) can be divided into two parts. One of them is proportional to the stickiness \( L \), which in turn is related to the mechanical composition of the soil through the specific surface \( \Omega_0 \) and the function associated with the particle size distribution \( D(w, \Pi_0) \). The other is proportional to the fraction of the solid phase \((1 - \Pi_0)\), because the improvement of the soil structure leads to a decrease in the friction force, as well as from the surface of contact with the liquid \( w^{2/3} \) and \((1 - \beta w)\). The proposed approach is fully consistent with the fact that the physical clay content (particles less than 0.01 mm) has a significant effect on the friction coefficient \( f \). Friction bond but with stickiness, which is directly proportional to the specific surface of the solid phase. Consequently, the coefficient of friction should be directly proportional to \( \Omega_0 \), i.e. the content of physical clay. After summarizing the above facts, you can use the phenomenological method to write the formula for the coefficient of soil friction:

\[
f = \alpha \Omega w^{2/3}(1 - \beta w)(1 - \Pi_0) + \gamma L, \tag{3}
\]

where \( f \) is the coefficient of friction; \( L \) is stickiness; \( \alpha, \beta, \gamma \) are empirical coefficients.

3. **Results and discussion**

The obtained dependencies of stickiness and friction forces for the black soil of the IAPC “Trud” of the Batyrevsky district, light gray and gray forest soils OJSC “Sormovo” of the Kanashsky region and light gray soil of the CJSC «Progress» of the Cheboksary district of the Chuvash Republic were analyzed together with dependencies for frictional forces. From the dependencies, the values of the “ripe” soil condition are determined from the moisture content of the initial sticking (i.e., the soil conditions are optimal for the mechanical impact on the soil). Moisture intervals corresponding to the soil conditions at which the mechanical impact on the soil is least effective are determined by the maximum adhesion moisture. The assessment of economic efficiency was carried out according to the methodological recommendations for assessing the economic efficiency of the introduction of new technologies and agricultural equipment. In addition, in some cases, for an objective comparative assessment of existing and proposed methods, the cumulative energy costs (direct and materialized indirect) are determined. Since the improvement and introduction of technologies is accompanied by additional capital investments, the introduction of new technologies and methods should ensure the improvement of quality and reduction of production costs together with the growth of labor productivity, that is, ensure the economic effect. The fuel consumption rate of a tractor is variable, depending on many factors, such as soil moisture, depth of processing, fuel system operability, condition of the tool's working parts, etc. The obtained dependences of friction coefficients on moisture for the main types of soil in the Chuvash Republic show that friction with optimal days of tillage conditions is 1.25-1.5 times less than the maximum value. Thus, the choice of optimal intervals for the mechanical impact on the soil allows, by reducing the traction resistance, saving about 5-7% of fuel.

Experimental verification of the ratio (3) for the main types of soil in the Chuvash Republic showed that the dependencies described are about 86.6% of experimental data (Figure 2).
Figure 2. Dependence of a friction coefficient on humidity for the main types of Chuvash Republic soils.

The study of the working modes of tillage machines (crumbling / speed) concerning various types of soil made it possible to determine the most effective moisture intervals at which, with an average fuel consumption of 4.1 to 17 l/ha, it saves from 0.16 to 0.68 l/ha. This makes it possible to reduce fuel consumption by 5-7 % and ensure the best mechanical effect on the soil (Table 1).

| tillage machine | depth (cm) | fuel economy (liter per hectare) |
|-----------------|------------|----------------------------------|
| K-701+          | 18-20      | 0.84-1.18                        |
| PTK-9-35        | 20-22      | 0.82-1.16                        |
|                 | 22-24      | 0.76-1.07                        |
| K-700+          | 18-20      | 0.76-1.05                        |
| PN-8-35         | 20-22      | 0.75-1.03                        |
|                 | 22-24      | 0.67-0.94                        |
| T-150K+         | 18-20      | 0.51-0.73                        |
| PLN-4-35        | 20-22      | 0.50-0.70                        |
|                 | 22-24      | 0.49-0.68                        |
| MTZ-82+         | 18-20      | 0.27-0.37                        |
| PLN-3-35        | 20-22      | 0.25-0.34                        |
|                 | 22-24      | 0.21-0.27                        |

Evaluation of economic efficiency was carried out according to the methodological recommendations for assessing the economic efficiency of the introduction of new technologies and
agriculture. In addition, in some cases, for an objective comparative assessment of existing and proposed methods, the cumulative energy costs (direct and materialized indirect) are determined. Since the improvement and introduction of technology are accompanied by additional capital investments, the introduction of new technologies and methods should ensure the improvement of quality and reduction of production costs together with the growth of labor productivity, that is, ensure the economic effect.

4. Conclusions
The results of the research can be substantially expanded by modeling the hydrophysical properties of the soil and studying the water and air regimes of the soils. In accordance with this important task there is the theoretical justification of the functional dependence of the frictional force in the soil on its specific surface, porosity and moisture for determining the moisture ranges at which meliorative measures are environmentally friendly and least energy intensive. The methodological basis was the fundamental and applied foundations of soil hydrophysics. The study of the modes of operation of the tillage machines (crumbling / speed) concerning various types of soils allowed determining the most effective moisture intervals at which, with an average fuel consumption from 4.1 to 17 l/ha, it is saved from 0.16 to 0.68 l/ha. This allows reducing fuel consumption by 5-7 % and to providing the best mechanical effect on the soil. The application of these methods was based on the use of modern software packages for processing the results of experiments conducted in laboratory and field conditions.

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