THE IMPACT OF SOIL MOISTURE AND COMPOSITION ON ITS PROPERTIES AND ENERGY CONSUMPTION OF TILLAGE

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INTRODUCTION

Energy consumption for soil tillage is determined by specific draft resistance of tillage machines. It is known from our previous investigation [1] that draft resistance of tillage machines depends on such soil properties as its hardness, density, friction and adhesion. These properties and tillage quality depend mainly on soil mechanical composition and moisture [2]. However, there are no correlations that would enable to determine draft resistance of tillage machines (ploughs, cultivators), depending on soil moisture and composition.

The purpose of the investigation is to evaluate soil properties and to estimate forces acting upon the surfaces of soil tillage machines as well as their draft resistance depending of soil moisture, mechanical composition and working speed.

OBJECTS AND METHODS

The object of the research is draft resistance of tillage machines, and tillage quality depending on their design parameters, as well as soil moisture and composition. On the basis of previous investigations [1], a computer algorithm has been worked out for the simulation of the forces exerted by soil upon operating (lifting and supporting) surfaces of tillage machines, and draft resistance caused by these forces. Tillage quality has been estimated by testing.

RESULTS

According to our earlier studies [1], draft resistance R_x of tillage machines is determined by share cutting resistance R_{Px}, the resistance caused by weight

R_{Gx} of the strip lifted, by inertia forces $R_{Jx,}$ soil adhesion R_{Ax} and weight R_{Qx} of the machine itself:

$$R_x = \Sigma\, R_{ix} = R_{Px} + R_{Gx} + R_{Jx} + R_{Ax} + R_{Qx}, \tag{1}$$

Vertical reaction R_z and lateral reaction R_y of the operating part are defined by corresponding partial reactions:

$$R_z = \Sigma\, R_{iz;} \qquad R_y = \Sigma\, R_{iy,} \tag{2; 3}$$

Total draft resistance R_x of the operating part is composed of the resistance of lifting (share-mouldboard) surface R_x' and the resistance of supporting (lower and lateral) surfaces R_x'':

$$R_x = R_x' + R_x'' = \sum R_{ix}' + f_0 \left(\sum R_{iz} + \sum R_{iy} + p_{Axy}\, S_{xy} + p_{Axz}\, S_{xz}\right) \tag{4}$$

where:

f_0 – is the coefficient of soil friction along working and supporting surfaces of the operating part,
p_{Axy} and p_{Axz} – specific adhesion forces, respectively, acting upon lower and lateral supporting surfaces of the operating part,
S_{xy}, S_{xy} and S_{xz} – surface areas of lower and lateral supporting surfaces of the operationg part, respectively.

Cutting resistance R'_{Px} is proportional to soil hardness ρ_0 and share edge surface area ω:

$$R'_{Px} = k_p\, \rho_0\, \omega = k_p\, \rho_0\, ib, \tag{5}$$

where:

k_p – a coefficient involving the impact caused by the shape of the share edge frontal surface,
i and b – edge thickness and width.

$$\rho_0 = \delta_0\, (b'' + d''m)\, e^{-l'' W^n}, \tag{6}$$

where:

ρ_0 – soil hardness characterising the resistance to the penetration of the flat round steel tip having a cross-section area of 1 cm^2, H/m^2,
δ_0 – soil (dried) density, kg/m^3,
m – the contents of physical clay (particles of the size < 0.01 mm, %),
W – absolute soil moisture, %,
B'', d'' and l'' – coefficients,
n – exponent,
e = 2.718…

For the investigation of soil the coefficients and the exponent entered into formula (6) have the following values: b''= 1100; d'' = 200; l'' = 4.10^{-3} and n = 2.

Hardness variations of soils having different mechanical composition that depends on their moisture is graphically presented in Figure 1.

For plough bodies mould-boards:

– Resistance caused by the weight of the lifted strip:

$$
\begin{aligned}
&R'_{Gx} \approx q\delta g k_y r \sin^{-1}\gamma \cdot \\
&\cdot\{ [(\sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma) e^{f_0 \sin\gamma(\varepsilon_1-\varepsilon_2)} - \\
&- (\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma)]\cos\varepsilon_1 + \\
&+ (\cos\varepsilon_1 e^{f_0\sin\gamma(\varepsilon_2-\varepsilon_1)} - \cos\varepsilon_2)(\cos\varepsilon_1 - f_0\sin\varepsilon_1\sin\gamma)^{-1}\cdot \\
&\cdot\sin\varepsilon_1\left[\sin\varepsilon_1\sin\gamma + f_0(\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)\right]\}
\end{aligned}
\tag{7}
$$

– Resistance caused by inertia forces:

$$
\begin{aligned}
&R'_{Jx} = q\delta v^2 k_y^{-1}\sin\gamma\{ (\sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma)\cdot \\
&\cdot e^{f_0\sin\gamma(\varepsilon_2-\varepsilon_2)} - (\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma) + \\
&+ (\cos\varepsilon_1 - f_0\sin\varepsilon_1\sin\gamma)^{-1} e^{f_0\sin\gamma(\varepsilon_2-\varepsilon_1)} \\
&\sin\varepsilon_1\left[\sin\varepsilon_1\sin\gamma + f_0(\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)\right]\}
\end{aligned}
\tag{8}
$$

– Resistance caused by soil adhesion:

$$
\begin{aligned}
&R'_{Ax} = p_A b r \sin^{-1}\gamma(e^{f_0\sin\gamma(\varepsilon_2-\varepsilon_1)} - 1)\cdot \\
&\cdot\{ \sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma + (\cos\varepsilon_1 - f_0\sin\varepsilon_1\sin\gamma)^{-1}\cdot \\
&\cdot\sin\varepsilon_1\left[\sin\varepsilon_1\sin\gamma + f_0(\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)\right]\}
\end{aligned}
\tag{9}
$$

where:

q – the area of cross section of the strip to be lifted,
δ – soil density,
k_y – soil compaction coefficient in front of the operating part,
f_0 – coefficient of soil friction against the surface of the operating element,
v – movement speed of the plough body,
p_A – specific force of soil adhesion to the operating surface,
b – surface width.

Soil density is dependent on strata density (mass of a volume unit of dried soil) δ_0 and soil moisture:

$$\delta = \delta_0\,(1 + W), \tag{10}$$

Observations indicate that the density of mineral soils generally varies from 1200 to 1800 kg/m^3. The resistance of the operating parts of soil tillage machines varies in proportion to soil density [1].

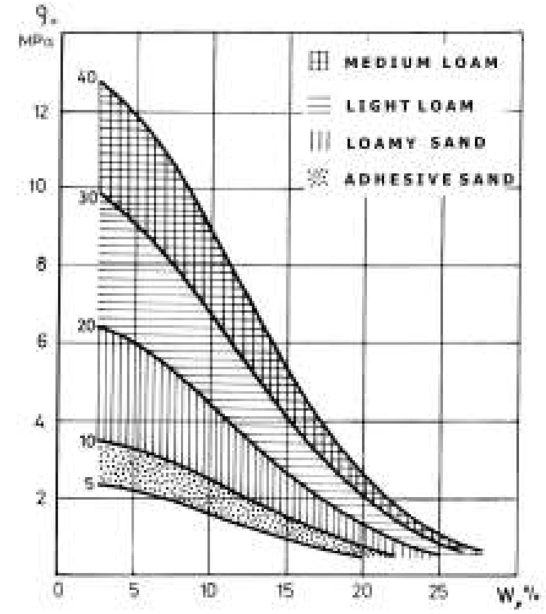

Fig. 1. Dependence of the hardness of soils having different mechanical composition on their moisture. Numbers at soil hardness curves stand for the percentage of physical clay in soil. Soil hardness is determined by Yu. Revyakin's hardness gage having a flat tip with a cross-section area 1 cm^2

As a rule, all the sources provide slipping resistance coefficients of soil. On the basis of these data, by the method of least squares, we have determined the coefficients of friction and specific adhesion force, after that the dependencies were deduced between them and the mechanical composition and moisture of soil:

$$f_0 = (a + e^{-[b_1 (b_2 - m)^2}) \, e^{-b_3 W^2} + (c + dm) \, e^{-[(k + l m)(t' + z' m - W)]^2}, \tag{11}$$

where:

a, b_1, b_2, b_3, c, d, k, l, t, z – the indices depending on the type of soil, material and condition of the surface of the object along which the soil slips,

$e = 2.718\ldots$,

W – absolute moisture of soil, %,

m – the content of physical clay in soil (particle size < 0.01 mm).

Variations in specific adhesion force p_A of soil correspond to the relation of the type:

$$p_A = (a' + p)\,(c' + d' m)\, e^{-[(k' + l' \mathrm{m})(t' + z' m - W)]^2} \tag{12}$$

where:

p_A – specific pressure of the layer (soil) upon the surface,

a', b', c', d', k', l', t', z' – indices depending on the type of soil, material and condition of the surface along which the soil slips.

The variations of the friction coefficient and specific force of soil adhesion to steel depending on moisture and mechanical composition of soil are presented in Figures 2 and 3.

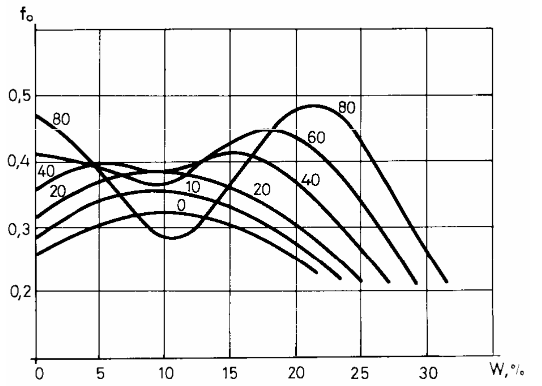

Fig. 2. Variations of friction coefficient of soils having different mechanical composition along steel depending on the moisture of soil. Numbers on the curves stand for percentage content of physical clay (particles smaller than 0.01 mm in size) in soil

Soil slipping resistance along steel depends on slipping speed, soil structure, humus content and surface temperature. The effect of these parameters may be considered by respective coefficients, e.g. velocity coefficients k_v and k_v':

$$k_v = k_{v\ top}\,[1 + a\,(1 + bv^n)^{-1}], \tag{13}$$

$$k_v' = k_v'_{top}\,[1 + a'\,(1 + b'v^{n'})^{-1}], \tag{14}$$

where:

$k_{v\ top}$ and $k_{v\ top}'$ – marginal value of velocity coefficient,
v – speed of slipping, m/s,
a, a' and b, b' – indices,
n and n' – exponents of indices.

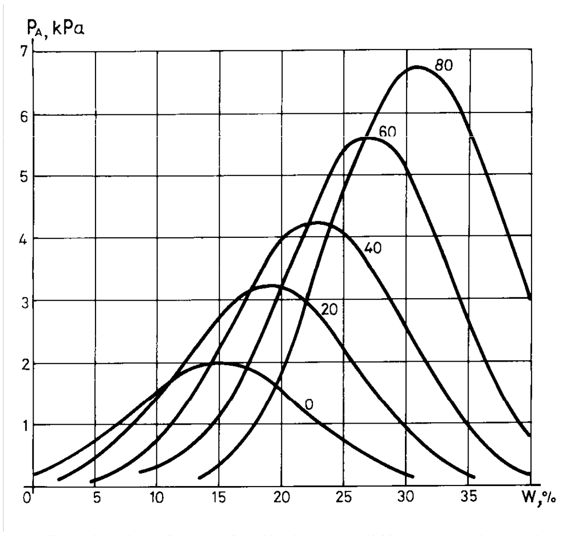

Fig. 3. Variations of specific adhesion force of soils having different mechanical composition along steel depending on the moisture of soil at the pressure of 100 kPa. Numbers on the curves stand for percentage content of physical clay (particles smaller than 0.01 mm in size) in soil

The variations of the coefficients indicating the influence of slipping speed a given type of soil are shown in Figure 4.

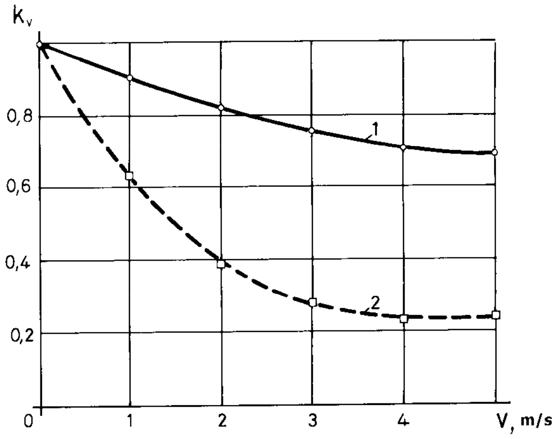

Fig. 4. Variations of coefficients indicating the influence of slipping speed upon friction coefficient and speci fic adhesion for wet soil: 1 – variations of coefficient k_v; 2 – variations of coefficient k_v'

There is insufficient amount of data for deriving mathematical dependencies characterising the influence of temperature upon the friction coefficient of soil along steel. When the temperature rises, specific adhesion force of soil to steel decreases forming a parabolic curve (on the basis of the data provided by H. G. Riek) described by the following relation:

$$p_A = p_{A_0} (1 - 10^{-4} t^2), \tag{15}$$

where:

p_{A_0} – specific adhesion force to steel at a temperature close to 0°C,

t – temperature of adhesive surfaces, °C.

There are no data either to deduce dependencies of the influence between the structure and humus content upon soil slipping resistance along steel. According to the data by H. G. Riek, if for a wet residual (paste-like) soil the coefficient of structurality k_s' is accepted as being 1, for a structured soil it will be 0.75-0.80.

The resistance caused by the weight and inertia forces of the lifted strip of soil is proportional to soil density and its friction coefficient.

The resistance caused by soil adhesion is proportional to the specific adhesion force between soil and the surface of the operating part.

Draft resistance caused by the weight of the machine itself is proportional to the friction coefficient.

Total draft resistance of the machine depends on its component resistances. The maximum resistance occurs in caked clay soils, the minimum – in sandy soils. The moisture increase in clay soils to 14-18% leads to their decreased resistance, yet at higher moisture it rises again.

The best tillage quality is also obtained at the optimum moisture.

CONCLUSIONS

1. The derived analytical correlations allow assessing draft resistance of soil tillage machines (ploughs, cultivators) depending on the value of soil moisture and composition, as well as on their design parameters and their working speed.

2. The correlations obtained allow determining the optimal soil moisture range when the tillage energy capacity is the lowest. In clay soils it varies from 14 to 18%. At this moisture level the tillage quality (degree of loosening) is also the best.

REFERENCES

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2. **Vilde A.**: Physical and mechanical properties of soil affecting energy capacity of its tillage. In: Proceedings of the 1st International Conference of BSB of ISTRO “Modern ways of soil tillage and assessment of soil compaction and seedbed quality”. 21-24 August 2001. EAU, Tartu, Estonia, 2001. p. 97-106.

SUMMARY

Two of numerous factors that influence soil properties and energy consumption are soil moisture and its composition. The correlations derived from our theoretical and experimental research allow to evaluate soil physical and mechanical properties such as density, hardness, friction, adhesion and to assess draft resistance of soil tillage machines (ploughs, cultivators) depending on the value of soil moisture and composition, as well as on design parameters and operating speed of the machines, and to determine the optimum range of soil moisture when the energy capacity of tillage is the lowest.