IMPACT OF SOIL HUMIDITY ON DRAFT RESISTANCE OF PLOUGH BODY

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Abstract. Ploughing is one of the most power consuming and expensive processes in agricultural production. It is known that the draft resistance of ploughs, the energy requirement for ploughing, the quality of ploughing and expenses depend on the plough body design, which is determined by the share-mouldboard parameters and the parameters of its supporting surfaces, as well as on such soil properties as its hardness, density, friction and adhesion, values of which are depending on soil mechanical composition, structure and humidity. Studies are carried out to determine the impact of the soil humidity on the ploughing resistance of the main soil types: sandy soil, loam and clay soils. It was cleared up that humidity most of all impacts the soil hardness and cutting resistance which considerably dominates in the summary resistance of the plough body. Increase in the soil humidity leads to decrease in the ploughing resistance that is more remarkable on clay soils. The working speed of the plough influences also the ploughing resistance. The optimum humidity of sticky clay soils when ploughing at the speed 2…2.5 m s^{-1} is 18…22 %.

Key words: ploughing resistance, impact of soil humidity, soil hardness, soil density, soil friction, soil adhesion, dynamics of soil properties.

Introduction

It is known that the ploughing resistance depends on the parameters of the plough body and such properties of soil as its hardness, density, friction and adhesion [1-5]. These properties and the tillage quality depend mainly on the mechanical composition and moisture of the soil. However, there were no correlations that would enable to determine the draft resistance of the tillage machines, such as ploughs, depending on the moisture and composition of soil.

The purpose of the investigation is to estimate the forces acting upon the surfaces of plough bodies, as well as their draft resistance and tillage quality in dependence of the soil moisture, its mechanical composition and the working speed of the plough.

Objects and methods

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

According to our earlier studies [1] the draft resistance R_x of the tillage machines is determined by the share cutting resistance R_{Px}, the resistance caused by weight R_{Gx} of the strip lifted, by the inertia forces R_{Jx}, by soil adhesion R_{Ax} and by the weight R_{Qx} of the machine itself:

$$R_x = \sum R_{Ix} = R_{Px} + R_{Gx} + R_{Jx} + R_{Ax} + R_{Qx} \tag{1}$$

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

$$R_z = \Sigma R_{iz}, \tag{2}$$

$$R_y = \Sigma R_{iy}. \tag{3}$$

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

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

where f_0 – the coefficient of soil friction along the working and supporting surfaces of the operating part;

p_{Axy}, p_{Axz} – specific adhesion forces, respectively, acting upon the lower and the lateral supporting surfaces of the operating part;
S_{xy}, S_{xz} – the surface areas, respectively, of the lower and the lateral supporting surfaces of the operating part.

Cutting resistance R_{Px} is proportional to soil hardness ρ_0 and the 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, b – the 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'', l'' – coefficients;
n – exponent;
$e \approx 2.718$.

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 $n = 2$.

At an inclined ploughshare a lateral reaction R_{Py} arises, its value being affected by the friction reaction:

$$R_{Py} = k_p \rho_0 Ib \operatorname{ctg} (\gamma_0 + \varphi_0) \tag{7}$$

Sumary cutting resistance:

$$R_{Px} = k_p \rho_0 Ib \, [1 + f_0 \operatorname{ctg} (\gamma_0 + \varphi_0)] \tag{8}$$

Forces caused by the gravity of the lifting soil slice:

$$\begin{aligned} R'_{Gx} \approx{} & q \delta g k_y r \sin^{-1} \gamma \cdot \{ [(\sin \gamma \cos \varepsilon_1 + \cos^2 \gamma \sin^{-1} \gamma) e^{f_0 \sin \gamma (\varepsilon_2 - \varepsilon_1)} - \\ & - (\sin \gamma \cos \varepsilon_2 + \cos^2 \gamma \sin^{-1} \gamma)] \cos \varepsilon_1 + (\cos \varepsilon_1 e^{f_0 \sin \gamma (\varepsilon_2 - \varepsilon_1)} - \cos \varepsilon_2)(\cos \varepsilon_1 - \\ & - f_0 \sin \varepsilon_1 \sin \gamma)^{-1} \sin \varepsilon_1 \cdot \left[\sin \varepsilon_1 \sin \gamma + f_0 (\sin^2 \gamma \cos \varepsilon_1 + \cos^2 \gamma) \right] \} \end{aligned} \tag{9}$$

$$R_{G_z} \approx q \delta g r \sin^{-1} \gamma \, (\varepsilon_2 - \varepsilon_1) \tag{10}$$

$$R_{G_y} \approx q \delta g r \sin^{-1} \gamma (\varepsilon_2 - \varepsilon_1)(\varepsilon_1 + 0.52)\, ctg \, \gamma \tag{11}$$

$$R''_{G_x} = f_0 (R_{Gz} + R_{Gy}) = F''_{Gx} \tag{12}$$

Forces caused by the soil inertia:

$$\begin{aligned} R'_{Jx} ={} & q \delta v^2 k_y^{-1} \sin \gamma \{ (\sin \gamma \cos \varepsilon_1 + \cos^2 \gamma \sin^{-1} \gamma) \cdot \\ & \cdot e^{f_0 \sin \gamma (\varepsilon_1 - \varepsilon_2)} - (\sin \gamma \cos \varepsilon_2 + \cos^2 \gamma \sin^{-1} \gamma) + + (\cos \varepsilon_1 - f_0 \sin \varepsilon_1 \sin \gamma)^{-1} e^{f_0 \sin \gamma (\varepsilon_2 - \varepsilon_1)} \cdot \\ & \cdot \sin \varepsilon_1 \left[\sin \varepsilon_1 \sin \gamma + f_0 (\sin^2 \gamma \cos \varepsilon_1 + \cos^2 \gamma) \right] \} \end{aligned} \tag{13}$$

$$R_{Jz} = q \delta v^2 k_y^{-1} \sin \gamma \sin \varepsilon_2 \, e^{f_0 \sin \gamma (\varepsilon_2 - \varepsilon_1)} \tag{14}$$

$$R_{Jy} \approx q \delta v^2 k_y^{-1} \sin \gamma \cos \gamma (1 - \cos \varepsilon_2) \tag{15}$$

$$R''_{Jx} = f_0 (R_{Jz} + R_{Jy}) = F''_{Jx} \tag{16}$$

Forces caused by soil adhesion:

$$R'_{Ax} = p_A\, b\, r \sin^{-1}\gamma\, (e^{f_0 \sin\gamma\, (\varepsilon_2 - \varepsilon_1)} - 1) * \{ \sin\gamma \cos\varepsilon_1 + \cos^2\gamma \sin^{-1}\gamma + (\cos\varepsilon_1 - f_0 \sin\varepsilon_1 \sin\gamma)^{-1} \cdot \cdot \sin\varepsilon_1 [\sin\varepsilon_1 \sin\gamma + f_0 (\sin^2\gamma \cos\varepsilon_1 + \cos^2\gamma)] \} \quad (17)$$

$$R_{Az} = 0; \quad (18)$$

$$R_{Ay} \approx 0; \quad (19)$$

$$R''_{Ax} = f_0\, (p_{Axy}\, S_{xy} + p_{Axz}\, S_{xz}) = F''_{Ax}. \quad (20)$$

where q – the cross section area of the soil slice;
δ – the density of soil;
k_y – the soil compaction coefficient;
f_0 – the soil friction coefficient;
v – the speed of ploughing;
p_A – the specific force of soil adhesion;
b – the surface width of the soil slice;
ε_1, ε_2 – correspondingly the initial and the final angles of the lifting (share- mouldboard) surface;
γ_0 – the inclination angel of the share edge; γ - the inclination angel of horicontal shape lines (generatrix);
g – acceleration caused by gravity (g = 9.81).

The draft resistance caused by the ploughs weight Q is proportional to the friction coefficient:

$$R''_{Qx} = Q\, f_0, \quad (21)$$

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

$$\delta = \delta_0\, (1+W). \quad (22)$$

Observations indicate that the density of mineral soils may vary in a very wide range: from 700 kgm^{-3} for dry, loose (freshly ploughed) soil to 2200 kg m^{-3} for wet, compact soil, but generally it varies from 1200 to 1800 kg m^{-3}. The resistance of the operating parts of the soil tillage machines varies in proportion to the soil density [2, 3].

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 dependencies were deduced between them and the mechanical composition, and moisture of soil [2-4]:

$$f_0 = (a + e^{-[\, b_1 (b_2 - m)^2}\,)\, e^{-b_3 W^2} + (c+dm)\, e^{-[\, (k + l\, m)\, (t' + z' m - W)]^2}, \quad (23)$$

where a, b_1, b_2, b_3, c, d, k, l, t, z – the indices depending on the type of soil, the material and the condition of the surface of the object along which the soil slides;
$e \approx 2.718$;
W – absolute moisture of soil, %;
m – the content of physical clay in soil (the particle size <0.01 mm), %.

Variations in the specific adhesion force p_A of soil correspond to the relation of the type [2-4]:

$$p_A = (a' + p)\, (c' + d' m)\, e^{-[\, (k' + l' m)\, (t' + z' m - W)]^2}, \quad (24)$$

where p_A – the specific pressure of the layer (soil) upon the surface;
a', b', c', d', k', l', t', z' – the indices depending on the type of soil, the material and the condition of the surface along which the soil slides.

The soil slide (slip) resistance along a steel surface depends on the sliding speed [4], the structure of soil, the humus content and the surface temperature. The effect of these parameters may be considered by respective coefficients. For example, the coefficients of velocity k_v and k'_v:

$$k_v = k_{v\,mrg}\, [1 + a\, (1 + b\, v^{\,n})^{-1}], \quad (25)$$

$$k_v{}^{/} = k_v{}^{/}{}_{mrg}\,[1 + a^{/}\,(1 + b^{/}\,v^{\,n^{/}})^{-1}], \tag{26}$$

where $k_{v\ mrg}$, $k_v{}^{/}{}_{mrg}$ – the marginal value of the velocity impact coefficient on the coefficient of friction and on the specific force of adhesion ;
v – the speed of sliding, m s^{-1};
a, $a^{/}$, b, $b^{/}$ – indices; n and $n^{/}$ – exponents of indices.

There is insufficient amount of data for deriving mathematical dependencies characterising the influence of temperature upon the friction coefficient of soil along a steel surface. When temperature rises, the 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 [3, 4]:

$$p_A = p_{A_0}\,(1 - 10^{-4}\,t^{2}), \tag{27}$$

where p_{A_0} – the specific adhesion force to a steel surface at a temperature close to 0^{o}C;
t – the temperature of the adhesive surfaces, ^{o}C .

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

The optimum humidity of soil at which the draft resistance will be minimal is determined by equating the first derivative of the function (1) to zero:

$$dR_x\,(dW)^{-1} = 0 \tag{28}$$

Because of the complexity of this equation in its full view, partial decisions can be used, and the optimum humidity of soil can be determined from the variables of the partial resistance depending on the humidity of soil, its mechanical structure, and the speed of work of the plough.

Results and discussion

The methods and equations given above allow for studying the regularities of the ploughing draft resistance depending on the humidity of soil, its mechanical composition, the plough body parameters, and its working speed.

As an example, comparative studies (simulation of the impact of the soil humidity on the ploughing resistance) have been done with plougs having semi-helicoidal bodies with the following main parameters:

- working width of the plough body b, 0.45 m
- depth of ploughing a, 0.20 m
- cross section area of the soil slice q, 0.09 m^2
- working speed v, 1-5 m s^{-1}
- working width of plough share b_s, 0.45 m
- thickness of the plough share i, 0.004 m
- initial inclination angle of the ploughshare to the furrow botom ε_1, 30 °
- final lifting angle of the share-mouldboard surface ε_2,100 °
- angle of the horicontal shape lines (generatrix) γ , 30, 40, 45 °
- radius of the share-mouldboard surface r, 0.5 m
- surface areas of the lower and the lateral supporting surfaces S_{xy} , S_{yz} , 0.02, 0.07 m^2

The indices of some soil properties used in the calculations are given in Tables 1 and 2.

Table 1

The indices of some soil properties used in calculations

Type of soil	Content of physical clay m, %	Humidity W, %	Density δ, кg m^{-3}	Coefficient of friction f_0	Specific force of adhesion p_A , Pa	Hardness ρ_0 , MPa
Loamy sand	10	5	1260	0.34	600	3.4
		10	1320	0.36	1600	2.5
		15	1380	0.33	2500	1.6
		20	1440	0.27	2300	0.8
Loam carbonate	30	5	1470	0.38	300	9.1
		10	1540	0.41	1100	6.7
		15	1600	0.40	2500	4.1
		20	1680	0.33	3600	2.0
		25	1750	0.24	3100	0.8
Clay	40	5	1575	0.40	200	12.0
		10	1650	0.38	800	8.9
		15	1725	0.41	2200	5.2
		20	1800	0.37	4000	2.8
		25	1875	0.27	4000	1.2
Clay dark chestnut (temno-kashtanovaya) [8]	63	5	1520	0.64	0	11.0
		10	1595	0.45	200	9.0
		15	1670	0.30	1100	6.5
		20	1740	0.30	3150	4.3
		25	1810	0.42	5400	2.0
		30	1875	0.62	5100	1.0

Table 2

Impact of speed on indices of soil properties parameters

Working speed v, m s^{-1}	Value of impact coefficients on:	
	soil friction coefficient along steel	specific force of adhesion
~0	1	1
1	0.9	0.63
2	0.82	0.40
3	0.76	0.28
4	0.71	0.23
5	0.69	0.23

The draft resistance of the plough body and its elements depending on the soil humidity at various working speeds and soil types is shown by the following graphs.

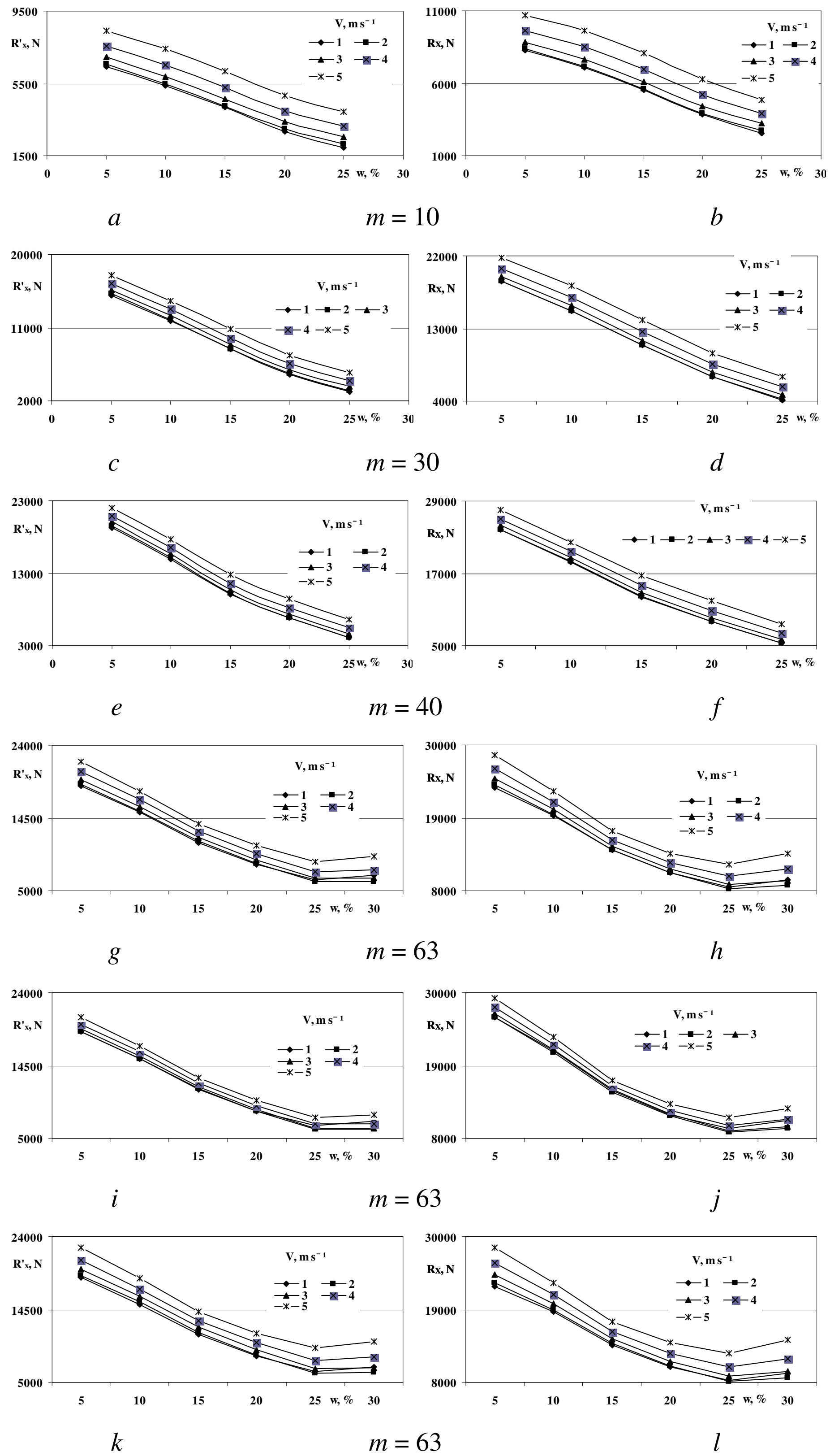

Fig. 1. **The draft resistance of the plough body depending on the soil humidity of some body types and speeds:** *a*, *c*, *e*, *g* – resistance of the share-mouldboard surface; *b*, *d*, *f*, *h* – total draft resistance at $\gamma = 40$ °; *i*, *j* and *k*, *l* – the same at $m = 63$ and $\gamma = 30$ °, $\gamma = 45$ °

The graphs above show that variations in the soil humidity have lesser impact on the plough body resistance on the light sandy-loam soils, but a considerable impact – on the clay soils. The clay soils show minima of the resistance at humidity – 18…22 %. Such a change of the ploughing resistance depending on the soil humidity is obtained also in the investigations by other researchers, for example, P. U. Bahtin [6, pp. 250-259], I. P. Mogilnij [7, p. 476] a.o.

Conclusions

1. The deduced analytical correlations and the developed computer algorithm allow for assessment of the forces acting upon the operating surfaces of the plough body and determination of its draft resistance depending on the value of the soil humidity and composition, as well as its design parameters and the working speed.
2. Presentation of the plough body draft resistance as the sum of the components – the cutting resistance of the soil slice, the resistance caused by its weight, the inertia forces and adhesion - allows for analysing the forces acting upon the share-mouldboard surface and suporting surfaces and their impact on the plough body draft resistance depending on the humidity and mechanical composition of soil, the body parameters and working speeds.
3. The value of the cuttingg resistance of the soil slice is dependent on the thickness of the share edge and has changes in acordance with the variations of the soil hardness. Variations in the draft resistance caused by the weight and inertia forces of soil correspond to the values of the friction resistance, but the resistance caused by the soil adhesion corresponds to the values of the specific force of its adhesion to the working share-mouldboard surfaces.
4. The correlations obtained allow for assessment of the ploughing resistance depending on the soil humidity, mechanical composition and the working speed of the plough, determination of the optimal soil humidity range when the tillage capacity is the lowest. Humidity most of all impacts the soil hardness and cutting resistance which considerably dominates in the summary resistance of the plough body. Increase in the soil humidity leads to decrease in the ploughing resistance that is more remarkable on clay soils. The optimum humidity of sticky clay soils when ploughing at the speed 2…2.5m s^{-1} is 18…22%.

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