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FORCES ACTING ON A PLOUGH BODY

Adolfs Rucins*, Arvids Vilde*, Wojciech Tanaś**

*Research Institute of Agricultural Machinery, Latvia University of Agriculture

** Department of Vehicles and Engines, Agricultural University of Lublin

Summary. By using analytical correlations derived as a result of theoretical research, a computer algorithm has been worked out for simulating the functions of a plough body and the forces exerted by soil upon the operating parts, as well as its draft resistance. These correlations allow to determine the forces acting on a plough body and its draft resistance depending on the body parameters, as well as to evaluate the impact of the physical and mechanical properties of soil upon it. They considerably influence the draft resistance of the body and, respectively, the energy capacity of ploughing and fuel consumption. The greatest influence upon the draft resistance is exerted by soil hardness, density and slip resistance along the surfaces of the operating parts. The speed increasing, the optimum inclination value of the horizontal generatrix for the minimum draft resistance decreases. In loamy soils, when the operating speed is 1…3 m s^{-1}, its optimum value is correspondingly 50…25^0.

The draft resistance of the supporting surfaces can reach 25…30% of the total plough body draft resistance or 42…54% of its share-mouldboard drafts resistance. The friction resistance constitutes 50–60% of the total resistance including the resistance of the supporting surfaces (25...30%).

Key words: forces acting on the plough body, draft resistance, analytic correlations, optimisation of parameters.

INTRODUCTION

It is known from our previous investigation [Vilde 1999, 2001] that the draft resistance of ploughs depends on such soil properties as its hardness, density, friction and adhesion. However, there were no analytical correlations that would enable to determine the draft resistance of the share-mouldboard surface and the plough body, as a whole, depending on their properties.

The purpose of the investigation is to estimate the forces acting upon the surfaces of the plough body and the impact of the physical and mechanical properties of soil on its draft resistance.

MATERIALS AND METHODS

The objects of the research are the forces acting on the plough body and its draft resistance depending on the body design parameters, as well as the physical and mechanical properties of the soil. On the basis of the previous investigations [Vilde 1999] a computer algorithm has been worked out [Ruciņš 2003] for the simulation of the forces exerted by soil upon the operating (lifting and supporting) surfaces of the plough body, and the draft resistance caused by these forces (Fig. 1).

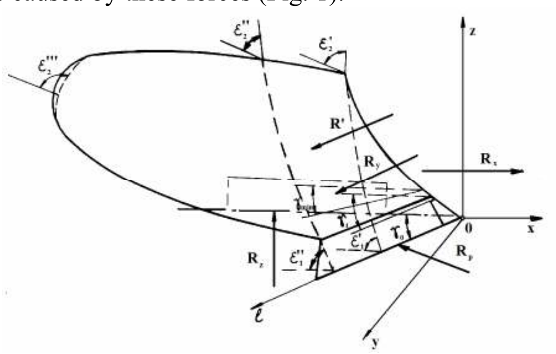


Fig. 1. A scheme of a plough body, its parameters and acting forces

According to our previous investigations [Vilde 1999], the draft resistance R_x of a plough body 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 weight R_{Qx} of the plough body itself (including a part of the weight of the plough). However, the latter is not dependent on the plough parameters.

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

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

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

The total draft resistance R_x of the operating part is composed of the resistance of the working surface $R^{/}_{x}$ and the resistance of the supporting (lower and lateral) surfaces $R^{//}_{x}$:

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

where:

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

p_{Axy} and p_{Axz} – specific adhesion force, respectively, to the lower and the lateral supporting surfaces of the operating part;

S_{xy} and S_{xz} – the surface area, respectively, of the lower and the lateral supporting surfaces of the operating part.

The friction resistance F_x is a constituent part of these reactions and their components [Ruciņš 2003], and by analogy we can write that

$$F'_x = \sum F'_{ix} = F'_{Px} + F'_{Gx} + F'_{Jx} + F'_{Ax} + F'_{Qx} = R'_x - R'_{xo} \ , \tag{5}$$

$$F''_x = f_0 (R_z + R_y + p_{Axy}\, S_{xy} + p_{Axz}\, S_{xz}) = R''_x , \tag{6}$$

$$F_x = F'_x + F''_x \, . \tag{7}$$

The friction resistance of the share-mouldboard surface is defined as the difference between the total resistance (general value of the partial resistance) and the resistance R_{xo} in operation without friction $(f_0 = 0)$.

$$F_{ix} = R_{ix} - R_{ixo} \ ; \quad F_x = R_x - R_{xo} \, , \tag{8; 9}$$

The ratio λ_F of the friction resistance in the partial and total resistance (reaction) is determined from their correlations:

$$\lambda_{F_{ix}} = F_{ix} \ R_{ix}^{-1} , \quad \lambda_{F_x} = F_x R_x^{-1} \, . \tag{10; 11}$$

The ratio λ_R of the supporting reactions in the partial and total draft resistance is determined from the correlation:

$$\lambda_{R_i} = R_i \ R_{ix}^{-1} . \tag{12}$$

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

$$R'_{Px} = k_p \rho_0 \, \omega = k_p \rho_0 \, ib \, , \tag{13}$$

where:

k_p – the coefficient involving the impact of the shape of the frontal surface of the ploughshare edge;

i and b – the thickness and width of the edge.

It is evident from formula (13) that the friction of soil along the edge does not influence the cutting resistance of the edge.

At a sharp ploughshare (the rear bevel is absent)

$$R_{Pz} = 0. \tag{14}$$

At a blunt (threadbare) ploughshare having rear bevel the vertical reaction R_{Pz} on the hard soils can reach the summary value of vertical reactions, this summary value arising from other forces acting on share-mouldboard surface (soil gravity and inertia) and weight of the body Q.

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

$$R_{Py} = k_p \rho_0 \, ib \, ctg \, (\gamma + \varphi_0) \,, \tag{15}$$

where:

γ – inclination angle of the edge towards the direction of movement (the wall of the furrow);

φ_0 – the angle of friction.

When friction is absent, $f_0 = 0$, $\varphi_0 = 0$ and

$$R_{Pyo} = k_p \rho_0 \, ib \, ctg \, \gamma \ . \tag{16}$$

Friction of soil along the ploughshare edge reduces the lateral pressure of the ploughshare (the pressure of the plough body against the wall of the furrow).

The resistance of the supporting surface

$$R^{//}_{Px} = k_p \rho_0 \, ib f_0 \, ctg \, (\gamma + \varphi_0) = F^{//}_{Px} \,. \tag{17}$$

The total cutting resistance

$$R_{Px} = k_p \rho_0 \, ib \, [1 + f_0 \, ctg \, (\gamma + \varphi_0)] \,. \tag{18}$$

The lateral cutting resistance of the knife is determined by formulae, similar to those for the cutting resistance from below. Consequently, similar to the above formulae will also be the formulae defining the impact of friction on the total resistance of the knife.

Forces caused by the weight of the lifting soil strip:

$$\begin{aligned} R'_{Gx} &\approx q\delta g k_y r \sin^{-1}\gamma \cdot \\ &\cdot \{ [(\sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma) e^{f_0 \sin\gamma(\varepsilon_1 - \varepsilon_2)} - \\ &-(\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma)]\cos\varepsilon_1 + \\ &+(\cos\varepsilon_1 e^{f_0\sin\gamma(\varepsilon_2-\varepsilon_1)} - \cos\varepsilon_2)(\cos\varepsilon_1 - f_0\sin\varepsilon_1\sin\gamma)^{-1} \cdot \\ &\cdot \sin\varepsilon_1 \left[\sin\varepsilon_1\sin\gamma + f_0(\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma) \right] \} \end{aligned} \tag{19}$$

$$R_{G_z} \approx q\delta g r \sin^{-1}\gamma \; (\varepsilon_2 \div \varepsilon_1) \tag{20}$$

$$R_{G_y} \approx q\delta g r \sin^{-1}\gamma \, (\varepsilon_2 - \varepsilon_1)(\varepsilon_1 + 0.52) \operatorname{ctg}\gamma \tag{21}$$

$$R''_{Gx} = f_0 \, (R_{Gz} + R_{Gy}) = F''_{Gx} \tag{22}$$

Forces caused by the soil inertia:

$$\begin{aligned} R'_{Jx} &= q\,\delta\, v^2 k_y^{-1} \sin\gamma \{ (\sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma) \cdot \\ &\cdot e^{f_0 \sin\gamma(\varepsilon_1-\varepsilon_2)} - (\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma) + \\ &+ (\cos\varepsilon_1 - f_0\sin\varepsilon_1\sin\gamma)^{-1} e^{f_0\sin\gamma(\varepsilon_2-\varepsilon_1)} \\ &\sin\varepsilon_1 \left[\sin\varepsilon_1\sin\gamma + f_0\,(\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)\right] \} \end{aligned} \tag{23}$$

$$R_{Jz} = q\,\delta\, v^2 k_y^{-1} \sin\gamma\,\sin\,\varepsilon_2\; e^{f_0\sin\gamma\,(\varepsilon_2-\varepsilon_1)}; \tag{24}$$

$$R_{Jy} \approx q\,\delta\, v^2 k_y^{-1} \sin\gamma\,\cos\gamma\,(1-\cos\varepsilon_2); \tag{25}$$

$$R''_{Jz} = f_0 (R_{Jz} + R_{Jy}) = F''_{Jx} \tag{26}$$

Forces caused by soil adhesion:

$$\begin{aligned} R'_{Ax} &= p_A\, b r \sin^{-1}\gamma\,(e^{f_0\sin\gamma\,(\varepsilon_2-\varepsilon_1)} - 1) \cdot \\ &\cdot \{ \sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma + (\cos\varepsilon_1 - f_0\sin\varepsilon_1\sin\gamma)^{-1} \cdot \\ &\cdot \sin\varepsilon_1 \left[\sin\varepsilon_1\sin\gamma + f_0(\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma)\right] \}; \end{aligned} \tag{27}$$

$$R_{Az} = 0\,; \tag{28}$$

$$R_{Ay} \approx 0\,; \tag{29}$$

$$R^{//}_{Ax} = f_0\,(p_{Axy}\,S_{xy} + p_{Axz}\,S_{xz}) = F^{//}_{Ax}\,. \tag{30}$$

where:

q – the cross section area of the strip to be lifted;
δ – the density of soil;
k_y – the soil compaction coefficient in front of the operating part;
f_0 – the soil friction coefficient against the surface of the operating element;
v – the speed of the movement of the plough body;
p_A – the specific force of soil adhesion to the operating surface;
b – the surface width of the soil strip;
ε_1 and ε_2 – correspondingly the initial and the final angles of the lifting (share-mouldboard) surface;
g – acceleration caused by gravity (g = 9.81).

The soil friction coefficient and the specific force of soil adhesion are not constant values. Their values decrease with an increase in speed [Vilde 2003]. This is considered in calculations.

The resistance of the supporting surfaces of the plough body depends on the values of the reacting forces. Yet their value is dependent, in many respects, on the manner of unification and perfection of the hydraulically mounted implements of the tractor. The vertical reaction of the plough with modern tractors having power regulation is transferred to the body of the tractor, and it affects the plough resistance to a considerably lesser degree. There are also solutions for the reduction of the lateral reaction. In such a way, the dominating component of the draft resistance of the plough body is the resistance of its share-mouldboard surface, to the research of which the present work is mainly devoted.

RESULTS

The presented work discusses, as an example, the research results of the forces acting on the plough body and the draft resistance caused by the share-mouldboard surface of the plough body at various angles γ of the horizontal generatrices depending on the speed of operation when ploughing loamy soils that predominate in Latvia.

The calculations were carried out with the computer according to the foregoing formulae.

The following values of the basic factors were taken into consideration, which affect the resistance of the share-mouldboard surface and the plough body.

Parameters of the plough body:	
Thickness of the share blade and knife	$i = 0.004$ m
The initial angle of the lifting strip of soil	$\varepsilon_1 = 30^0$
The final angle of the lifting strip of soil	$\varepsilon_2 = 100^0$
The angle between the horizontal generatrix of the operating surface and the vertical longitudinal plane	$\gamma = 15^0 \ldots 90^0$
The radius of the curvature of the lifting surface	$r = 0.5$ m
The area of the lower supporting surface	$S_{xy} = 0.0157$ m^2
The area of the lateral supporting surface	$S_{xz} = 0.068$ m^2
The weight of the plough body	$Q = 200$ kg
Physical and mechanical properties of soil:	
The hardness of soil	$\rho = 4.1$ MPa
The density of soil	$\delta = 1600$ kg/m^3
The coefficient of soil friction against the surface of the operating element	$f_0 = 0.4$
The adhesion force	$p_{A0} = 2.5$ kPa
The mode and status of work:	
The ploughing depth	$a = 0.20$ m
The cross section area of the lifted soil strip	$q = 0.07$ m^2
The soil compaction coefficient in front of the operating part	$k_y = 1.1$
The working speed	$v = 1 \ldots 5$ m s^{-1}.

The inclination angle γ of the horizontal generatrix of the real share-mouldboard surfaces of plough bodies lies between $26^0 \ldots 50^0$. Steeper surfaces ($\gamma > 50^0$) refer to the slanting blades of bulldozers.

The calculation results of the draft resistance of the lifting surface and its components are presented in Fig. 2–5, the reacting forces on the supporting surfaces – in Fig. 6–8, the draft resistances of the share-mouldboard and supporting surfaces - in Fig. 9–10 and the total draft resistance of the plough body – in Fig. 11.

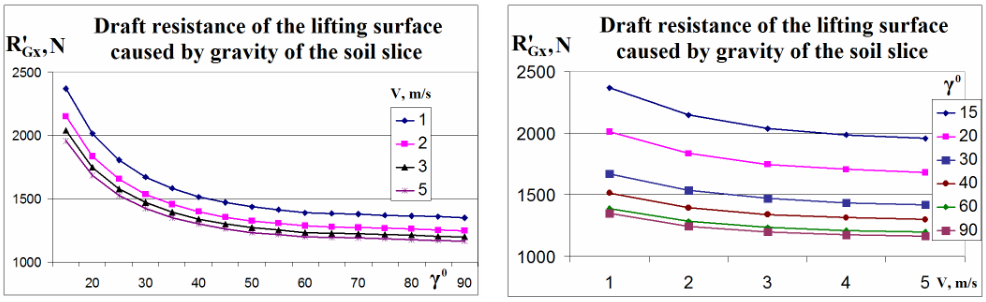


Fig. 2. Draft resistance of the lifting surface caused by the gravity of the soil slice depending on speed v and the inclination angle γ of the horizontal generatrix

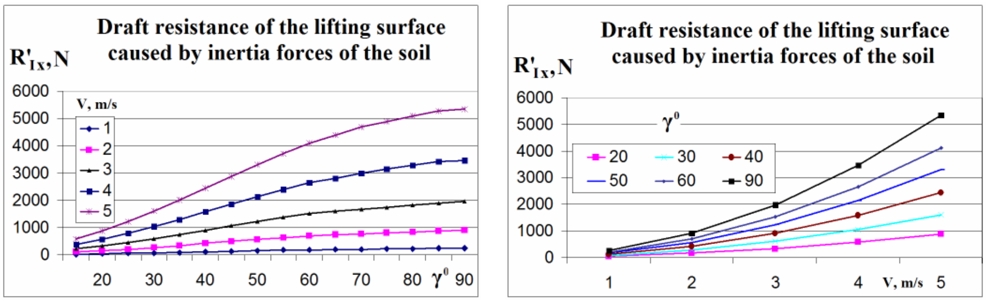


Fig. 3. Draft resistance of the lifting surface caused by the soil inertia forces of the soil slice depending on speed v and the inclination angle γ of the horizontal generatrix

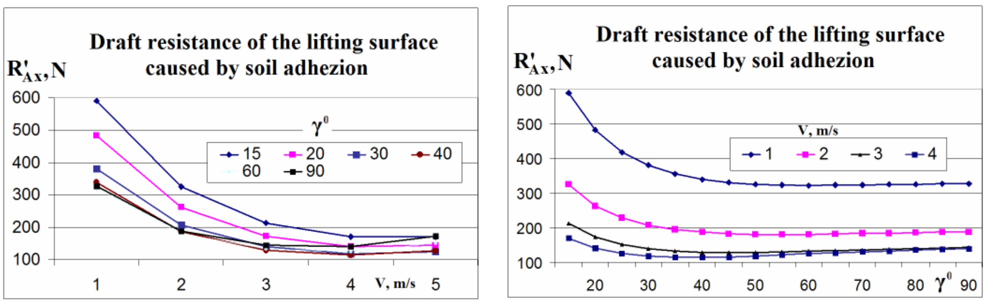


Fig. 4. Draft resistance of the lifting surface caused by soil adhesion depending on speed v and the inclination angle γ of the horizontal generatrix

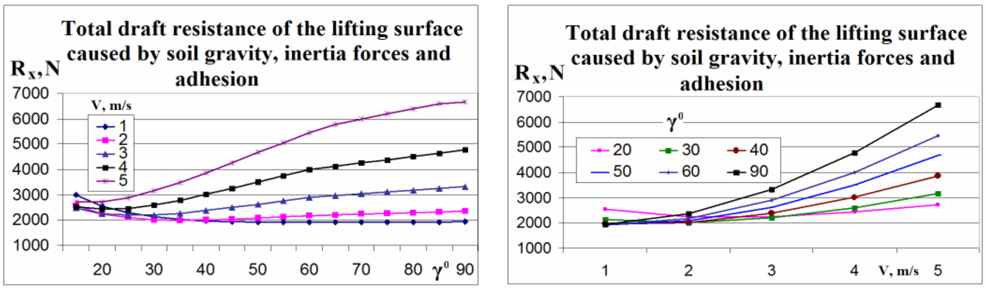


Fig. 5. Total draft resistance of the lifting surface caused by soil gravity, inertia forces and adhesion depending on speed *v* and the inclination angle *γ* of the horizontal generatrix

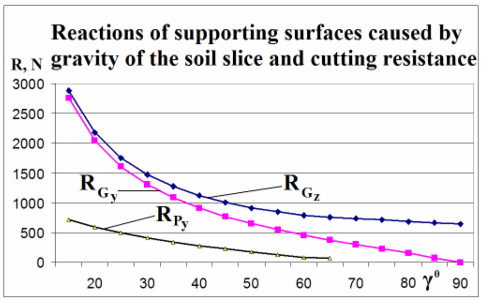


Fig. 6. Reactions of the lower and lateral supporting surfaces caused by gravity of the soil slice and share cutting resistance depending on the inclination angle *γ* of the horizontal generatrix

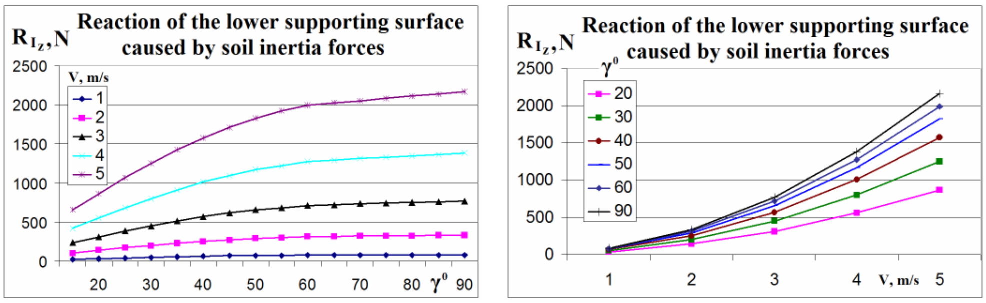


Fig. 7. Reaction of the lower supporting surface caused by soil inertia forces depending on speed *v* and the inclination angle *γ* of the horizontal generatrix.

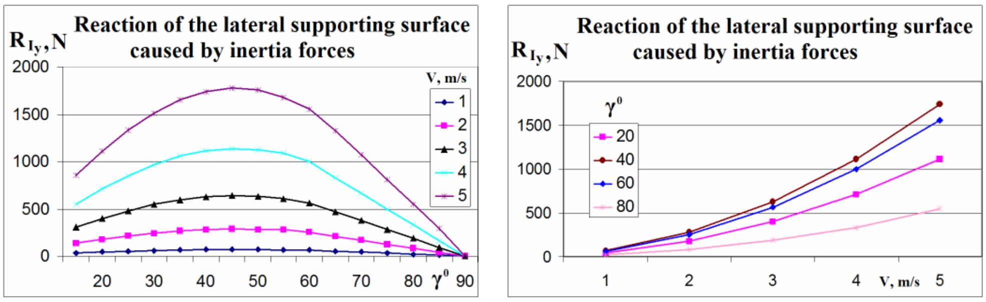


Fig. 8. Reaction of the lateral supporting surfaces caused by soil inertia forces depending on speed *v* and the inclination angle *γ* of the horizontal generatrix

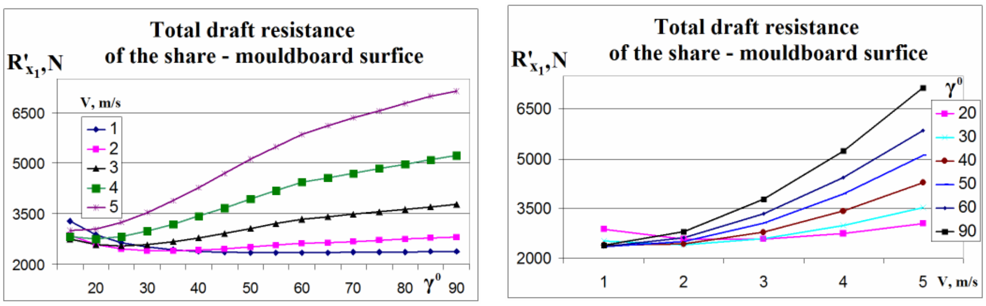


Fig. 9. Total draft resistance of the share-mouldboard surface caused by soil gravity, inertia forces, adhesion and share cutting resistance depending on speed *v* and the inclination angle *γ* of the horizontal generatrix

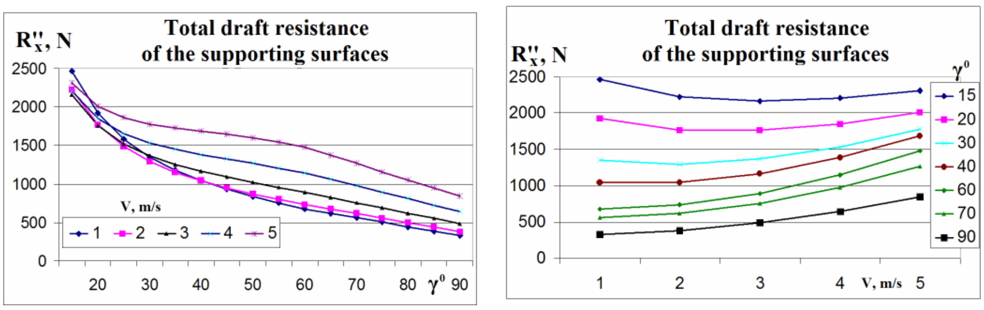
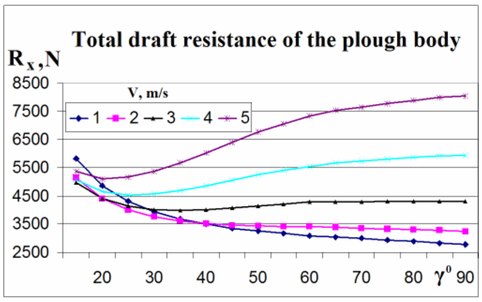


Fig. 10. Total draft resistance of the supporting surfaces depending on the speed *v* and the inclination angle *γ* of the horizontal generatrix



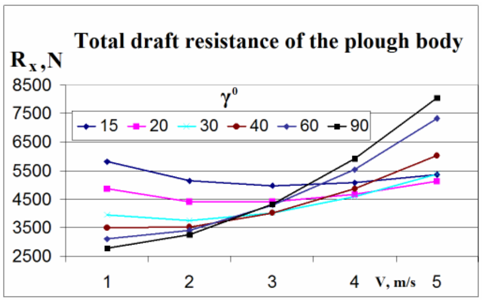


Fig. 11. Total draft resistance of plough body depending on speed *v* and the inclination angle *γ* of the horizontal generatrix

The material of the calculations presents the values and correlations of the changes in the forces acting on the share-mouldboard and the supporting surfaces, the draft resistance of the share-mouldboard, and the supporting surfaces, as well as the total resistance of a plough body and its components under working conditions depending on the working speed *v* and the inclination angle *γ* of the horizontal generatrix.

It follows from the figures that the values of resistances caused by the weight and soil adhesion decrease with the increase in the operation speed (Fig. 2 and 4). This can be explained by the reduction of the friction coefficient and the specific adhesion force of soil while the speed of its slipping along the share-mouldboard surface increases. The resistance caused by the soil inertia forces increases when speed increases (Fig. 3), and at speeds over 3…4 m s^{-1} these inertia forces start dominating over all the other components. When speed increases (up to the speed of 2…2.5 m s^{-1}), the summary draft resistance of the share-mouldboard surface increases insignificantly, then grows faster (Fig. 5 and 9). At a steeper share-mouldboard surface (at great values of angle *γ*) this growth is more remarkable and intense. In wet loamy soils there may be cases (at quite a flat share-mouldboard surface) when the draft resistance does not increase but even decreases whereas the speed increases (within the range of 1…2 m s^{-1}). Such a phenomenon may occur when the decrease in resistance due to the lower friction coefficient and specific soil adhesion proceeds more intensely than the growth in the resistance caused by the soil inertia forces within the given range of speeds.

When the inclination of the generatrix (angle *γ*) is increased, resistances because of the soil weight and adhesion fall but the resistance due to the inertia forces increases, particularly in operation at higher speeds. The decrease of the first ones can be explained by the fact that at a steeper share-mouldboard surface its length decreases and because of this there is a decrease in the mass of soil slipping along it. Decreasing the area of its surface leads to a lower resistance due to soil adhesion. As a result, the total draft resistance of the share-mouldboard surface shows a marked minimum, which at a greater operating speed moves towards lower inclination values of the horizontal generatrix. Thus, increasing the speed from 1 to 3 m s^{-1}, the optimum value of angle *γ* of the share-mouldboard surface decreases from 50^0 to 25^0 (Fig. 9).

From the presented example it is evident (Fig. 10 and 11) that the draft resistance of the supporting surfaces is considerable. It can reach 25…30% of the total plough body draft resistance, or 42…54% of its share-mouldboard draft resistance (Fig. 10 and 9).

The impact of the soil-metal friction upon the plough body draft resistance is significant, too. It may reach 50…60% of the total draft resistance including the resistance of the supporting surfaces (25…30%).

In such a way, the deduced analytical correlations and the developed computer algorithm allow simulation of soil coercion upon the share-mouldboard surface of the plough body, taking into consideration its draft resistance in determining the optimum parameters (the inclination of the horizontal generatrix) at minimum resistance.

CONCLUSIONS

1. The deduced analytical correlations and the developed computer algorithm allow simulation of the soil coercion forces upon the operating surfaces of the plough body, determination of the draft resistance and the optimum values of parameters.
2. Presentation of the plough body draft resistance as the sum of components – the cutting resistance of the strip, the resistance caused by its weight, the soil inertia forces and adhesion - allows analysing the forces acting upon the share-mouldboard surface, finding out the character of their changes depending on speed and the parameters of the surface, and assessment of their ratio in the total resistance.
3. Increase in the inclination of the horizontal generatrix leads to a decrease in the draft resistance caused by the weight and adhesion of soil but it increases the resistance caused by inertia forces, particularly, when the speed increases. The inclination of the generatrix (the edge of the share) does not affect the cutting resistance of the strip.
4. In loamy soils, when the speed grows from 1 to 3 m s^{-1}, the optimum value of the inclination angle between the horizontal generatrix of the share-mouldboard surface and the wall of the furrow decreases from 50^0 to 25^0.
5. The draft resistance of the supporting surfaces is considerable. It can reach 25..30% of the total plough body draft resistance, or 42...54% of its share-mouldboard draft resistance.
6. The impact of the soil-metal friction upon the draft resistance of the plough body is significant, too. It may reach 50…60% of total draft resistance including the resistances of the supporting surfaces (25…30%).

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