DRAFT RESISTANCE OF THE PLOUGHS DEPENDING ON SOIL FRICTION

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Abstract

By using analytical correlations derived as a result of theoretical research, a computer algorithm has been worked out for simulating the functions of the plough body and the forces exerted by soil upon the operating parts, as well as its draft resistance. These correlations allow to determine the draft resistance of the plough depending on the parameters of its body, as well as to evaluate the impact of the physical and mechanical properties of soil, such as friction upon it. The greatest influence upon the draft resistance is exerted by soil hardness, density and slip resistance along the surfaces of the operating parts. The latter is also affected by soil adhesion, which particularly manifests itself in wet clay soils at lower temperatures. It has been clarified that the friction resistance constitutes 46 – 62% of the total draft resistance of the plough body. The main ways of lowering the friction resistance and the total draft resistance of the plough are the introduction of a more rational design of its body having optimum parameters, decreasing the resistance of the share-mouldboard surface and the values of reactions of the supporting surfaces, as well as the application of antifriction materials and better modes of joining with tractors.

Key words: plough draft resistance, friction resistance, analytic correlations, optimisation of parameters.

Introduction

It follows from our previous investigations (Vilde 1999, 2003, 2004; Rucins and Vilde 2003, 2004) that the draft resistance of ploughs depends on the body parameters, the physical and mechanical properties of soil, and the working modes. However, there were not enough investigations for analytic assessment of the impact of the body parameters and the variability of soil properties, such as friction, on the variations in the ploughing resistance. This encumbers the calculation of the proper solution of the plough body design and raising the ploughing efficiency.

The purpose of these investigations was analytical assessment of the impact of the variability of the plough body parameters and the soil friction properties on the variations in the ploughing resistance in order to determine the optimal body design under particular soil conditions to improve the ploughing efficiency.

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 soil and the working modes. On the basis of previous investigations, a computer algorithm has been worked out 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).
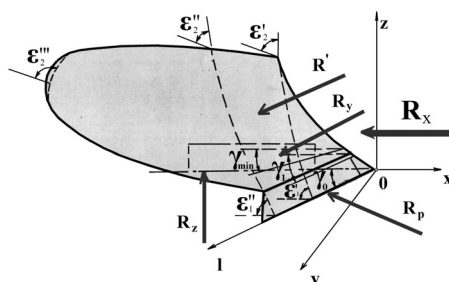

Fig. 1. Scheme of the plough body, its parameters and acting forces.

According to our previous investigations (Vilde, 1999), the draft resistance R_x of the plough body is determined by the share of the cutting resistance R_{Px}, the resistance caused by the gravity (weight) R_{Gx} of the soil slice 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):

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

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

$$R_z = \sum R_{iz}; \quad R_y = \sum R_{iy}; \quad R_x = R'_x + R''_x = \sum R'_{ix} + f_0 \left(\sum R_{iz} + \sum R_{iy} + p_{Axy} S_{xy} + p_{Axz} S_{xz} \right), \tag{2; 3; 4}$$

where: f_0 – the coefficient of the soil friction along the working and supporting surfaces of the plough body;

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

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

The friction resistance F_x is a constituent part of these reactions and their components (Rucins et al., 2003), and, by analogy, we can write that

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

$$F''_x = f_0 (R_z + R_y + p_{Axy} S_{xy} + p_{Axz} S_{xz}) = R''_x; \qquad F_x = F'_x + F''_x. \tag{6; 7}$$

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

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

Ratio λ_F of the friction resistance in the partial and total resistance (reaction), as well as ratio λ_R of the supporting reactions in the partial and total draft resistance is determined from their correlations:

$$\lambda_{F_i x} = R_i - R_{ix}{}^{-1}; \qquad \lambda_{Fx} = Fx - R_{ix}{}^{-1}; \qquad \lambda_{R_i} = R_i - R_{ix}{}^{-1}. \tag{10; 11; 12}$$

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 friction of soil along the edge does not influence the cutting resistance.

At a sharp ploughshare (the rear bevel is absent)

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

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

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

$$R_{Py} = k_p \rho_0 ibctg(\gamma_0 + \varphi_0), \tag{15}$$

where: γ_0 – the inclination angle of the edge towards the direction of the movement (the wall of the furrow);

φ_0 – the angle of friction.

When friction is absent,
$$f_0 = 0, \quad \varphi_0 = 0, \quad R_{Py0} = k_p \rho_0 ibctg\gamma_0. \tag{16}$$

The 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 and the total cutting resistance is:

$$R''_{Px} = k_p \rho_0 ibf_0 ctg(\gamma_0 + \varphi_0) = F_{Px}'', \text{ and } R_{Px} = k_p \rho_0 ib\left[1 + ctg(\gamma_0 + \varphi_0)\right] \tag{17; 18}$$

The lateral cutting resistance of the knife is determined by formulae, similar to those for the cutting resistance of the share. 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 gravity of the lifting soil slice:

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

$$R_{Gy} \approx q\delta g r \sin^{-1}\gamma(\varepsilon_2 - \varepsilon_1)(\varepsilon_1 + 0.52)\, ctg\,\gamma, \tag{20}$$
$$R_{Gz} \approx q\delta g r \sin^{-1}\gamma(\varepsilon_2 - \varepsilon_1), \tag{21}$$
$$R''_{Gx} = f_0(R_{Gz} + R_{Gy}) = F''_{Gx}; \tag{22}$$

forces caused by the soil inertia:

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

$$R_{Jz} = q\,\delta v^2 k_y^{-1}\sin\gamma\sin\varepsilon_2\, e^{f_0\sin\gamma(\varepsilon_2-\varepsilon_1)}, \tag{24}$$
$$R_{Jy} \approx q\,\delta v^2 k_y^{-1}\sin\gamma\cos\gamma(1 - \cos\varepsilon_2), \tag{25}$$
$$R''_{Jx} = f_0(R_{Jz} + R_{Jy}) = F''_{Jx}; \tag{26}$$

forces caused by soil adhesion:

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

$$R_{Az} = 0, \qquad R_{Ay} \approx 0, \tag{28; 29}$$
$$R''_{Ax} = f_0(p_{Axy}S_{xy} + p_{Axz}S_{xz}) = F'', \tag{30}$$

where: q – the cross section area of the soil slice; δ – the density of soil; ky – 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; b – the surface width of the soil slice; ε_1 and ε_2 are correspondingly the initial and the final angles of the lifting (share–mouldboard) surface;

g – acceleration caused by gravity ($g = 9.81$).

The draft resistance caused by the ploughs weight Q:

$$R''_{Qx} = Qf_0. \qquad (31)$$

The soil friction coefficient and the specific force of soil adhesion are not constant values. Their values decrease with the increase in speed (Rucins et al., 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 and Discussion

The presented work discusses, as an example, the results of the impact of the body parameters, the physical and mechanical properties of soil, such as the soil friction and the working modes, on the draft resistance of the plough body at various

initial lifting angles ε_1, and at various angles γ of the horizontal generatrices, and at various working widths depending on the speed of operation when ploughing, for example, loamy soils, which predominate in Latvia (Rucins and Vilde 2004, 2005).

Calculations were carried out with a computer according to the foregoing formulae.

As an example, the calculation results of the impact of the soil friction coefficient f_0 upon the draft resistance of the plough body share-mouldboard (lifting) surface, as well as reacting forces on the supporting surfaces, the draft resistance and the total draft resistance of the entire plough body at the inclination angle $\varepsilon_1 = 30°$ of the share (initial soil slice lifting angle), at the inclination angle $\gamma = 30°…50°$ of the horizontal generatrix and at various speeds v are presented in the Figs 2 – 12.

The draft resistance of the lifting (share-mouldboard) surface and its components are presented in Figs 2 – 5, the reacting forces on the supporting surfaces – in Figs 6 – 10, the draft resistances of the supporting surfaces – in Fig. 11, and the total draft resistance of the plough body – in Fig. 12.
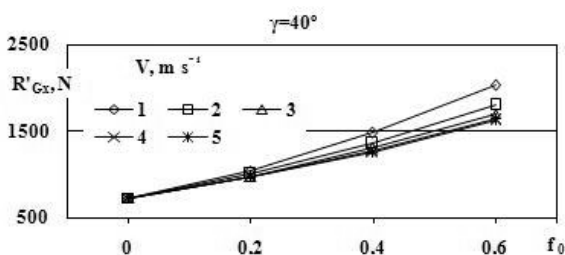

Fig. 2. Impact of the soil friction coefficient f_0 upon the draft resistance of the plough body share–mouldboard surface caused by the gravity of the soil slice.
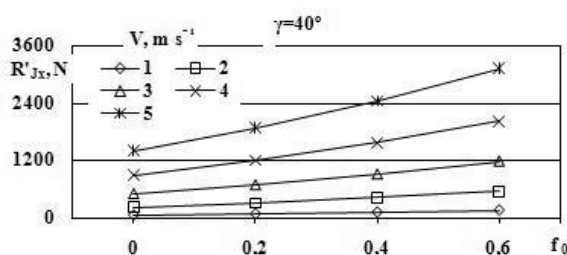

Fig. 3. Impact of the soil friction coefficient f_0 upon the draft resistance of the plough body share–mouldboard surface caused by the soil inertia forces.
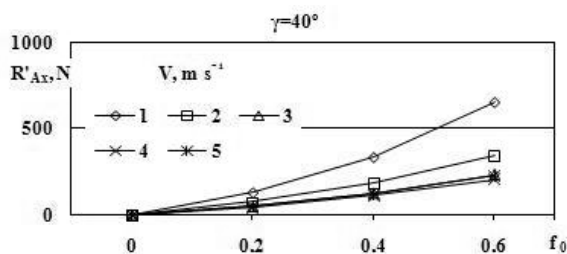

Fig. 4. Impact of the soil friction coefficient f_0 upon the draft resistance of the plough body share-mouldboard surface caused by adhesion.
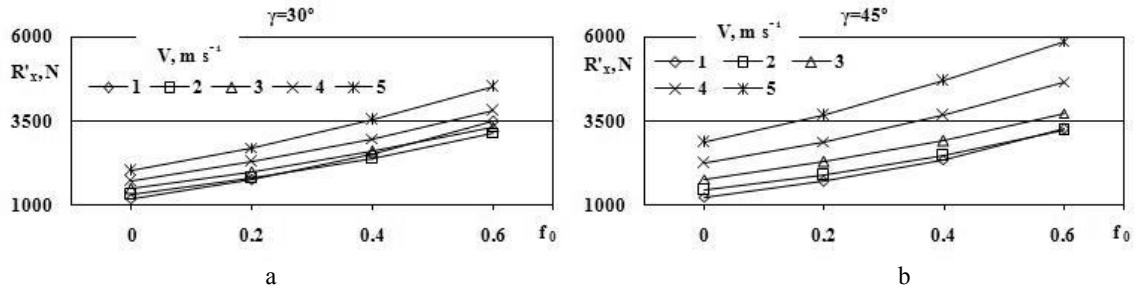
261

Fig. 5. Impact of the soil friction coefficient f_0 upon the total draft resistance of the plough body share–mouldboard surface caused by the soil gravity, the inertia forces, adhesion and soil cutting resistance at the inclination angle γ of the horizontal generatrix: a – γ =30°; b – γ =45°.

From Figs 2–5 it follows that at the soil friction coefficient f_0 = 0.3...0.4 and at the speed v=2...3 m s^{-1}, presently predominating in ploughing, the draft resistance caused by the soil friction takes 36...42% of the total draft resistance of the share–mouldboard surface.
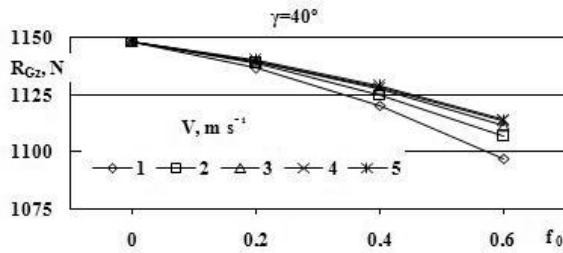

Fig. 6. Impact of the soil friction coefficient f_0 upon the vertical reaction of the plough body caused by the gravity of the soil slice.
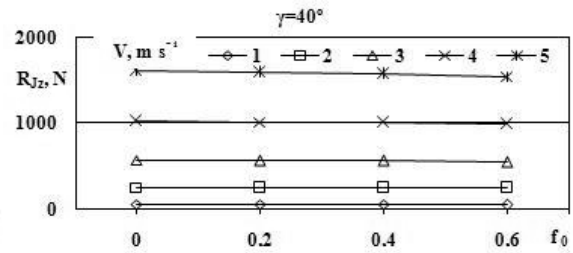
Fig. 7. Impact of the soil friction coefficient f_0 upon the vertical reaction of the plough body caused by the inertia forces of the soil slice.
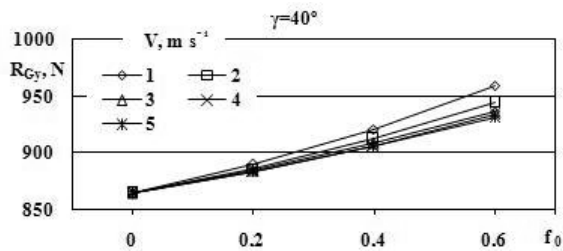

Fig. 8. Impact of the soil friction coefficient f_0 upon the lateral reaction of the plough body caused by the gravity of the soil slice.
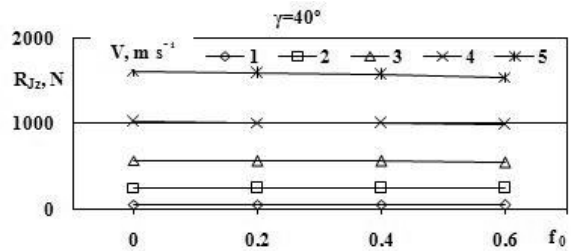
Fig. 9. Impact of the soil friction coefficient f_0 upon the lateral reaction of the plough body caused by the inertia forces of the soil slice.

The calculations and Figs 6–9 show that the value of the soil friction caused at the soil slice gravity, inertia forces and adhesion has only a little influence on the reactions of the supporting surfaces.
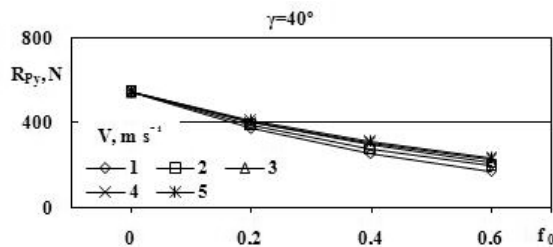

Fig. 10. Impact of the soil friction coefficient f_0 upon the lateral reaction caused by the soil cutting with the plough share at the inclination angle of the cutting edge γ_0 = 40°.

Fig. 10 shows that at the values of the friction coefficient f_0 = 0.3...0.4 the lateral reaction caused by the soil cutting decreases on 36...55%.
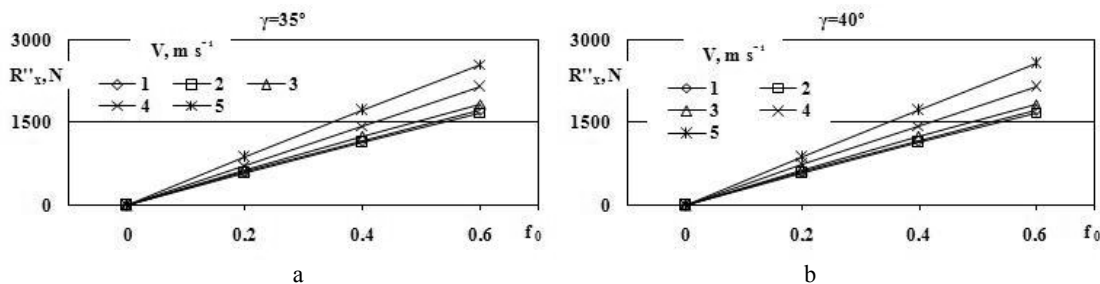
Fig. 11. Impact of the soil friction coefficient f_0 upon the draft resistance of the supporting surfaces of the plough body: a – γ =35°; b – γ = 40°.

It follows from Fig. 11 that the increase in speed increases the draft resistance of the supporting surfaces caused by soil friction. The value of the inclination angle of the horizontal genetratrix γ at the interval $\gamma = 35°…45°$ has only a little influence on the draft resistance of the supporting surfaces.

It follows from Fig. 12 that at the values of the friction coefficient $f_0 = 0.3…0.4$ the draft resistance caused by the soil friction takes 46…62% of the total draft resistance of the plough body. It follows that the total draft resistance is approximately proportional to the friction coefficient. Increasing the speed decreases the share (ratio λ_f) of the friction resistance in the total draft resistance of the plough body. This phenomenon can be explained by the decreasing value of the friction coefficient when the speed is increasing (Vilde et al. 2007).

Fig. 12 also shows that at the values of the friction coefficient $f_0 = 0.3…0.4$, increasing the inclination angle of the horizontal genetratrix γ in the interval $\gamma = 35°…45°$, increases the draft resistance of the plough body to 6…10 %. This phenomenon is in agreement with the previous conclusions that the optimal values for the inclination angle of the horizontal genetratrix γ on the initial part of the share–mouldboard surface are 34…38° (Rucins et al., 2007).

It follows from formulae (17) – (30), too, that increasing the initial lifting angle ε_1 increases the draft resistance of the share-mouldboard surface, including the resistance of the soil friction (Rucins et al., 2007), but increasing the working width of the body decreases the specific draft resistance of ploughing (Rucins and Vilde, 2005). It was established from the formulae that the optimal values of the initial lifting angle are $\varepsilon_1 = 28…32°$ and the optimal working width of the plough body $b = 45…50$ cm.

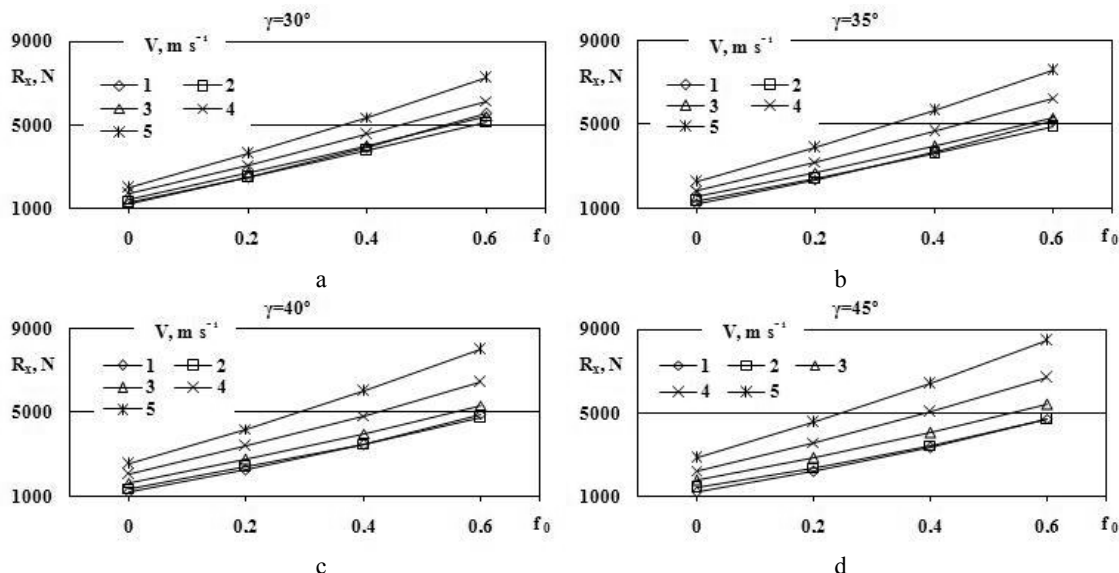

Fig. 12. Impact of the soil friction coefficient f_0 upon the total draft resistance of the plough body: a – γ =30°; b – γ = 35°; c – γ = 40°; d – γ = 45°.

From the presented example it is evident that the draft resistance of the supporting surfaces is considerable. It can reach 25…30% of the total plough body draft resistance, or 36…44% of its share-mouldboard draft resistance (Figs 5, 11, 12).

Therefore it is very important for the reduction of the energy consumption of ploughing to reduce the draft resistance of the supporting surfaces. It may be obtained by using a contemporary hang-up device with the tractors, for example, power regulation allowing the transfer of the vertical reactions of the plough to the body of the tractor. It may decrease the draft resistance of the ploughs to 6…10%.

In the sources provided by other authors there are no materials about the application of the simulation methods in order to study the impact of the plough body parameters, as well as the soil friction properties on the draft resistance of the plough bodies. In order to obtain a better design of the plough body, a series of different bodies were built and tested (Larsen, 1968; Бурченко et al., 1976; Бурченко, 2001, Nikiforov and Ivanov, 1973). Yet it is bound with a great loss of resources, labour and time, so the best solution of the compared variants may not always be the optimum ones.

The materials of our investigations carried out by using the correlations indicated above present the values and regularity of the changes in the forces, the soil friction, 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 the plough body and its components under the working conditions depending on the body parameters, the soil friction coefficient and the working speed. In such a way it is possible to discover the draft resistance structure of the body, to assess the ratio of each element in the total resistance, to search and find possibilities how to reduce the tillage energy requirement.

Conclusions

1. The deduced analytical correlations and the developed computer algorithm allow assess the soil coercion forces upon the operating surfaces of the plough body, determinate the draft resistance and the optimal values of parameters, as well as the impact of the soil friction properties.

2. Presentation of the plough body draft resistance as the sum of its components – the cutting resistance of the soil slice, the resistance caused by its gravity, the soil inertia forces and adhesion including the soil friction resistance – allows analysing the forces acting upon the share-mouldboard and the supporting surfaces, finding out the character of their changes depending on the soil properties, parameters of the surfaces, of working speed, assessment of their ratio in the total resistance and determination of the optimal parameters of the body.

3. Increase in the inclination of the horizontal generatrix leads to a decrease in the draft resistance caused by the weight, adhesion and friction of the soil but it increases the resistance caused by the 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 soil slice.

4. The impact of the soil–metal friction upon the draft resistance of the plough body is significant. It may reach 46…62% of the total draft resistance including the resistances of the supporting surfaces (25…30%). Therefore measures will be taken to diminish it, for example, by improving the body design, improving the mode of aggregation (joining) with tractors, using antifriction materials. The relief of the lower supporting surface may diminish the draft resistance of the body caused from the soil friction to 6…10%.

5. The optimal values of the main parameters of the body for contemporary ploughs, working at the speeds of 2…2.5 m s^{-1} are: the inclination angle of the share towards the furrow bottom – 28…32^0; the inclination angle of the horizontal generatrix towards the furrow wall on the initial part of the share-mouldboard surface – 34…38^0, on the top – not less than 48^0; the working width of the bottom – 45…50 cm.

6. The use of bodies having optimal parameters allows obtaining a good ploughing quality, reduction of the draft resistance by 12…20% and a corresponding rise in the efficiency, saving fuel and financial means.

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