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Impact of Friction on the Plough Body Draft Resistance

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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 body's draft resistance, friction resistance, analytic correlations, optimisation of parameters.

INTRODUCTION and LITERATURE REVIEW

It follows from our previous investigations *(Vilde, 1999, 2003, 2004; Rucins and Vilde, 2004, 2005, 2007)* 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 purposes 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.

MATERIAL and METHOD

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 (Figure 1).

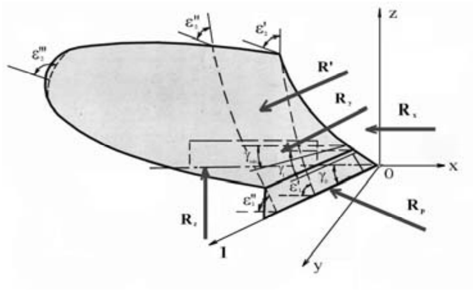


Figure 1. Scheme of the plough body, its parameters and acting forces.

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).

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

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

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

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.

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

where: f_0 is 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 and Vilde, 2005)*, and, by analogy, we can write that

$$F'_x = \sum F'_{ix} = F'_{Px} + F'_{Gx} + F'_{Jx} + F'_{Ax} = R'_x - R'_{xo} \qquad (5)$$

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

$$F_x = F'_x + F''_x \qquad (7)$$

The friction resistance of the share-mouldboard surface is defined as the difference between the total resistance R'_x and resistance R'_{xo} in operation without friction (f_0=0).

The cutting resistance R'_{Px} is proportional to soil hardness ρ_0 and the share edge surface area $\omega = ib$:

$$R'_{Px} = k_p \rho_0\, \omega = k_p \rho_0\, ib \qquad (8)$$

where: k_p is 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.

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

$$R_{Py} = k_p \rho_0\, ib\, ctg\, (\gamma_0 + \varphi_0) \qquad (9)$$

where: γ_0 is the inclination angle of the edge towards the direction of the movement

φ_0 - the angle of friction.

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

$$R_{Pyo} = k_p \rho_0\, ib\, ctg\, \gamma_0 \qquad (10)$$

The friction of soil along the ploughshare edge reduces the lateral pressure of the ploughshare.

The resistance of the supporting surface

$$R''_{Px} = k_p \rho_0\, ib\, f_0\, ctg\, (\gamma_0 + \varphi_0) = F''_{Px} \qquad (11)$$

The total cutting resistance is:

$$R_{Px} = k_p \rho_0\, ib\, [1 + f_0\, ctg\, (\gamma_0 + \varphi_0)] \qquad (12)$$

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:

$$\begin{aligned} R'_{Gx} \approx\ & q\delta g k_y r \sin^{-1}\gamma \{ [(\sin\gamma \cos\varepsilon_1 + \\ & + \cos^2\gamma \sin^{-1}\gamma) e^{f_0 \sin\gamma(\varepsilon_2 - \varepsilon_1)} - \\ & - (\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma)] \cos\varepsilon_1 + \\ & + (\cos\varepsilon_1 e^{f_0 \sin\gamma(\varepsilon_2-\varepsilon_1)} - \cos\varepsilon_2)(\cos\varepsilon_1 - \\ & - f_0 \sin\varepsilon_1 \sin\gamma)^{-1} \sin\varepsilon_1 * \\ & * \left[\sin\varepsilon_1 \sin\gamma + f_0 (\sin^2\gamma \cos\varepsilon_1 + \cos^2\gamma) \right] \} \end{aligned} \qquad (13)$$

$$R_{Gz} \approx q\delta g k_y r \sin^{-1}\gamma\, (\varepsilon_2 - \varepsilon_1) \qquad (14)$$

$$R_{Gy} \approx q\delta g k_y r \sin^{-1}\gamma\, (\varepsilon_2 - \varepsilon_1)(\varepsilon_1 + 0.52)\, ctg\,\gamma \qquad (15)$$

$$R''_{Gx} = f_0\, (R_{Gz} + R_{Gy}) = F''_{Gx} \qquad (16)$$

Forces caused by the soil inertia:

$$\begin{aligned} R'_{Jx} =\ & q\,\delta v^2 k_y^{-1} \sin\gamma \{ (\sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma) * \\ & * e^{f_0 \sin\gamma(\varepsilon_2-\varepsilon_1)} - (\sin\gamma\cos\varepsilon_2 + \cos^2\gamma\sin^{-1}\gamma) + \\ & + (\cos\varepsilon_1 - f_0 \sin\varepsilon_1 \sin\gamma)^{-1} e^{f_0 \sin\gamma(\varepsilon_2-\varepsilon_1)} * \\ & * \sin\varepsilon_1 \left[\sin\varepsilon_1 \sin\gamma + f_0\, (\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma) \right] \} \end{aligned} \qquad (17)$$

$$R_{Jz} = q\ \delta\ v^2 k_y^{-1} \sin\gamma\, \sin\varepsilon_2\ e^{f_0 \sin\gamma\, (\varepsilon_2-\varepsilon_1)} \qquad (18)$$

$$R_{Jy} \approx q\ \delta\ v^2 k_y^{-1} \sin\gamma\, \cos\gamma\, (1 - \cos\varepsilon_2) \qquad (19)$$

$$R''_{Jx} = f_0 (R_{Jz} + R_{Jy}) = F''_{Jx} \qquad (20)$$

Forces caused by soil adhesion:

$$\begin{aligned} R'_{Ax} =\ & p_A\, b\, r \sin^{-1}\gamma\, (e^{f_0 \sin\gamma\, (\varepsilon_2-\varepsilon_1)} - 1) * \\ & * \{ \sin\gamma\cos\varepsilon_1 + \cos^2\gamma\sin^{-1}\gamma + (\cos\varepsilon_1 - f_0 \sin\varepsilon_1 \sin\gamma)^{-1} * \\ & * \sin\varepsilon_1 \left[\sin\varepsilon_1 \sin\gamma + f_0 (\sin^2\gamma\cos\varepsilon_1 + \cos^2\gamma) \right] \} \end{aligned} \qquad (21)$$

$$R_{Az} = 0; \qquad R_{Ay} \approx 0; \qquad (22), (23)$$

$$R''_{Ax} = f_0\, (p_{Axy} S_{xy} + p_{Axz} S_{xz}) = F''_{Ax} \qquad (24)$$

where: q - the cross section area of the soil slice;

γ – the angle of the horizontal shape-lines;

δ - the density of soil;

k_y - the soil compaction coefficient in front of the operating part;

f_0 - the soil friction coefficient;

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 body's weight Q:

$$R^{//}_{Qx} = Q f_0 \tag{25}$$

The soil friction coefficient and the specific force of soil adhesion are not constant values. Their values decrease with the increase in speed *(Vilde at al., 2007).* This is considered in calculations.

The inclination angle γ lies between $26^0 \ldots 50^0$. Steeper surfaces ($\gamma > 50^0$) refer to the slanting blades of bulldozers.

RESULTS and DISCUSSION

The presented work discusses, as an example, the simulation results of the impact of the body parameters, the soil friction and the working modes on the draft resistance of the plough body at various initial lifting angles ε_1, at various angles γ of the horizontal shape-lines (generatrices) and at various working widths depending on the speed of operation when ploughing, for example, loamy soils, which predominate in Latvia.

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 and resistance on the supporting surfaces, and the total draft resistance of the entire plough body at the inclination angle ε_1=30° of the share (initial soil slice lifting angle), at the inclination angle γ=35°...45° of the horizontal shape-lines and at various speeds v are presented in the following graphs.

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

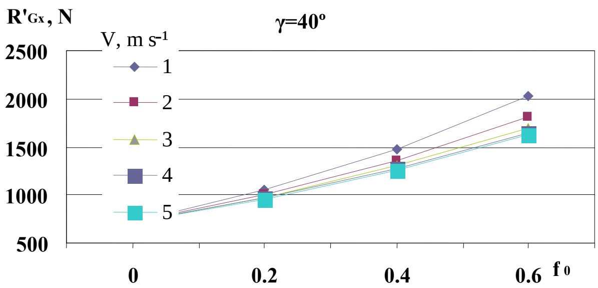


Figure 2. Impact of the soil friction coefficient f_0 upon the draft resistance of the plough body share-mouldboard surface caused by the gravity of the soil slice.

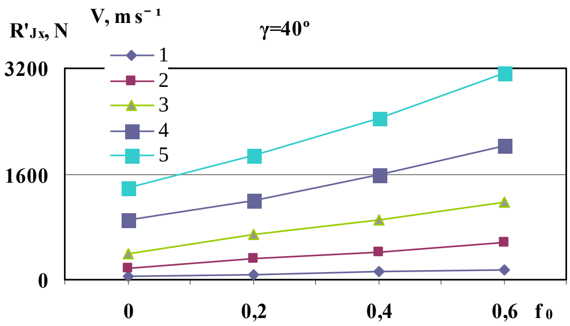


Figure 3. Impact of the soil friction coefficient f_0 upon the draft resistance of the plough body share-mouldboard surface caused by the soil inertia forces.

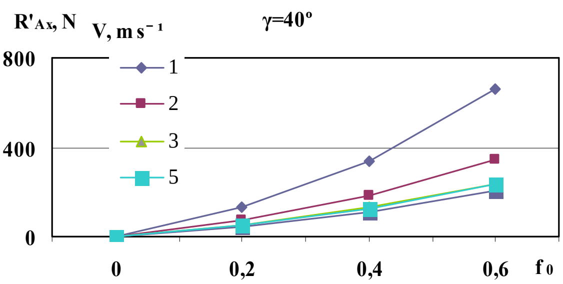
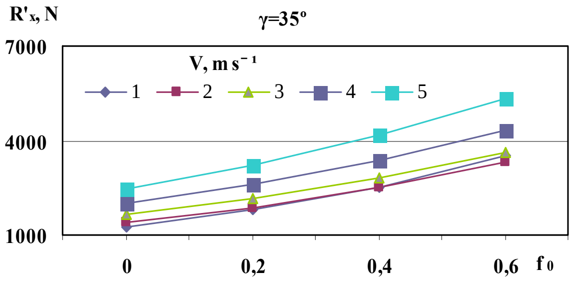


Figure 4. Impact of the soil friction coefficient f_0 upon the draft resistance of the plough body share-mouldboard surface caused by adhesion.



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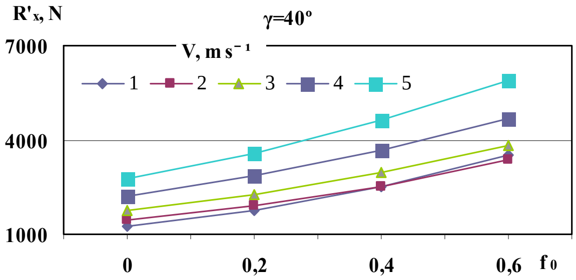

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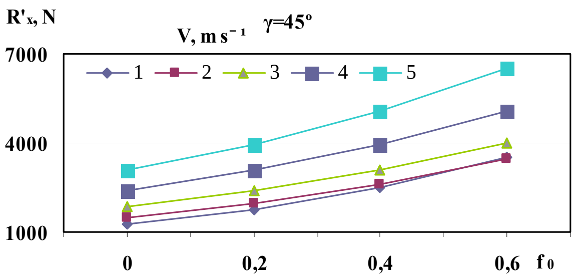

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Figure 5. Impact of the soil friction coefficient f_0 upon the total draft resistance of the plough body share-mouldboard surface caused by the soil gravity, the inertia forces, adhesion and soil cutting resistance at the inclination angle γ of the horizontal generatrix: a – γ=35°; b - γ=40°; c - γ=45°

From the graphs above (Figures 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.

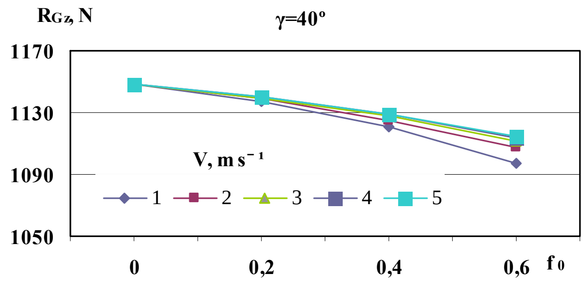


Figure 6. Impact of the soil friction coefficient f_0 upon the vertical reaction of the plough body caused by the gravity of the soil slice.

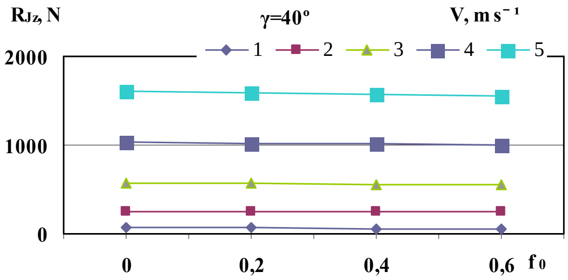


Figure 7. Impact of the soil friction coefficient f_0 upon the vertical reaction of the plough body caused by the inertia forces of the soil slice.

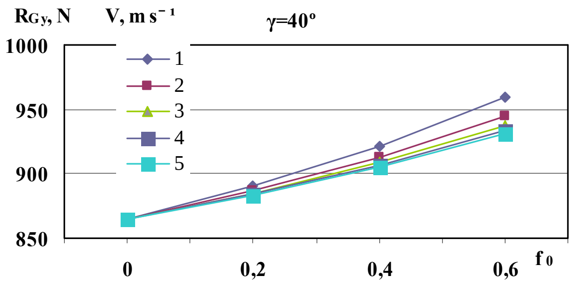


Figure 8. Impact of the soil friction coefficient f_0 upon the lateral reaction of the plough body caused by the gravity of the soil slice.

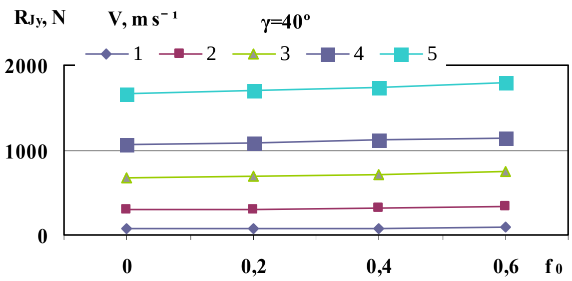


Figure 9. Impact of the soil friction coefficient f_0 upon the lateral reaction of the plough body caused by the inertia forces of the soil slice.

The calculations and graphs above (Figures 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.

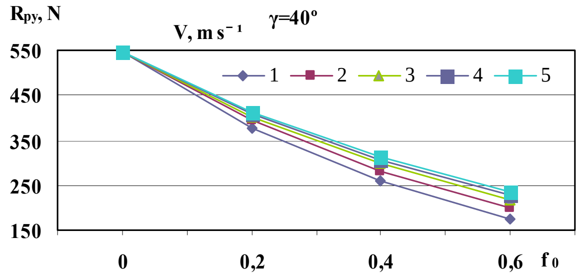
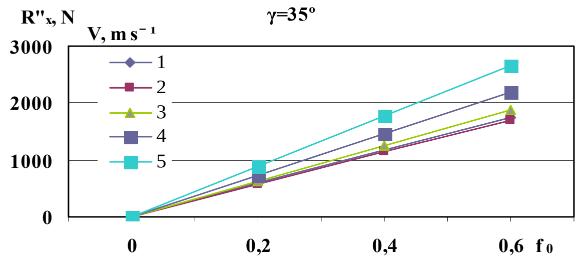


Figure 10. Impact of the soil friction coefficient f_0 upon the lateral reaction caused by the soil cutting with the plough share at the inclination angle of the cutting edge γ^0 =40°.

The graph above (Figure 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%.



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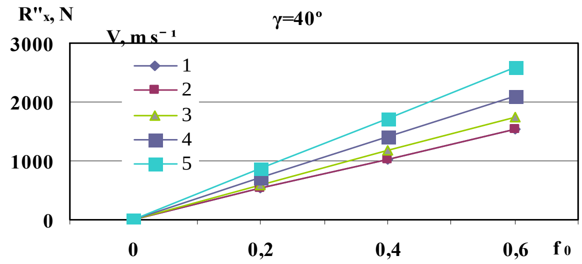

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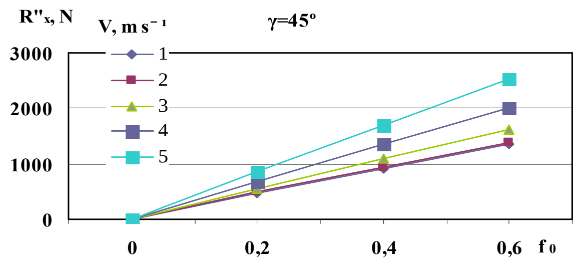

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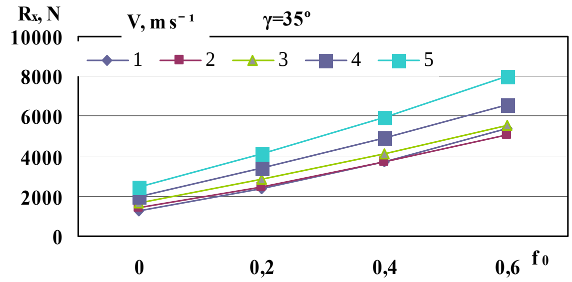
Figure 11. Impact of the soil friction coefficient f_0 upon the draft resistance of the supporting surfaces of the plough body: a - γ =35°; b - γ =40°; c - γ =45°.

It follows from the graphs above (Figure 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 γ = 35°...45° has only a little influence on the draft resistance of the supporting surfaces.



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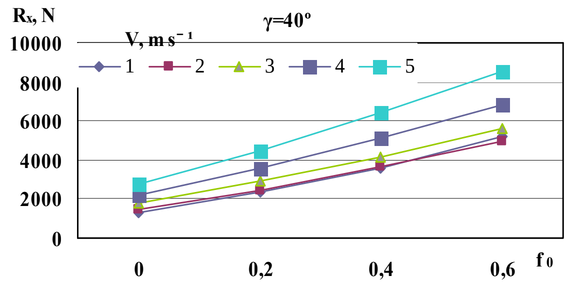

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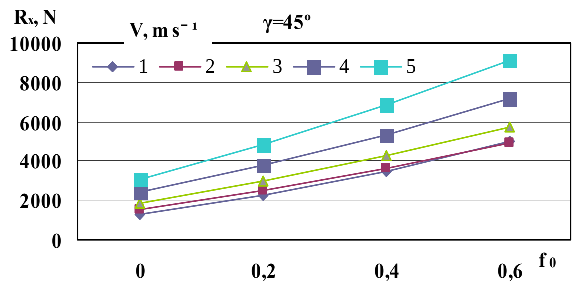

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Figure 12. Impact of the soil friction coefficient f_0 upon the total draft resistance of the plough body: a - γ =35°; b - γ =40°; c - γ =45°

It follows from the graphs above (Figure 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 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).*

From the graphs (Figure 12) it is evident too that at the values of the friction coefficient f_0 = 0.3...0.4 increasing the inclination angle of the horizontal shape-lines γ in the interval γ = 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 shape-lines γ on the initial part of the share-mouldboard surface are 34…38^0 *(Rucins and Vilde, 2007)*.

It follows from formulas (15)-(21), 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 and Vilde, 2007)*, but increasing the working width of the body decreases the specific draft resistance of ploughing *(Rucins and Vilde 2005)*. It was established from them that the optimal values of the initial lifting angle are ε_1=28...32° and the optimal working width of the plough body – b = 45...50 cm.

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 (Figures 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 *(Vilde, 2004)*. 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; Burchenko et al., 1976; 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 simulation of the soil coercion forces upon the operating surfaces of the plough body, determination of 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 shape-lines (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.

7. Further, in such a way it is possible to carry out the simulation of the impact of the soil moisture, as well as of the other soil properties, on the work and the draft resistance of the ploughs with aim to find out the favourable soil conditions for efficient ploughing.

REFERENCES

Burchenko, P.N., A.N. Ivanov; B.A. Kashajev, V.G. Kirjuhin, A.I. Miltsev, 1976. Resultaty issledovanija rabochih organov skorostnyh plugov. In *Povyshenie rabochih skorostjei mashinno-traktornyh agregatov.* Moscow, Kolos: 215-218. (In Russian). "Results of the investigation of the working parts of high-speed ploughs".

Larsen, L.W., W.G. Lovely, C.W. Bockup. 1968. Predicting draught forces using model mouldboard ploughs in agricultural soils. *Trans. American Society of Agricultural Engineers*, 11: 665-668.

Nikiforov, P.E. and A.N. Ivanov, 1973. Issledovanije rabochih organov plugov dlja raboty so skorostjami 10-15 km/h. In *Povyshenie rabochih ckorostjei mashinno-traktornyh agregatov.* Moscow, CINTIAM: 197-203. (In Russian). "Investigation of the working parts of ploughs for working at the speeds of 10-15 km/h".

Rucins, A., A. Vilde, 2004. Mathematical modelling of the operation of plough bodies to determine their draft resistance and optimum parameters. *TEKA Commission of Motorization and Power Industry in Agriculture, Volume IV.* Polish Academy of Sciences Branch in Lublin. Lublin, Poland: 177–184.

Rucins, A., A. Vilde, 2005. Modelling forces acting on the plough body. *Simulation in Wider Europe. 19th European Conference on modelling and Simulation ECMS 2005 June 1-4, 2005 Riga, Latvia.* Riga: 414-419.

Rucins, A., A. Vilde, 2005. Plough body working width optimization. *Recent results and future challenges in soil tillage research. International scientific seminar Reports.* Akademija, Lithuania: 69-75.

Rucins, A., A. Vilde, 2007. Impact of the Plough Body Parameters on the Ploughing Efficiency. *Ecology and Agricultural Machinery. Proceedings of the 5th International Scientific and Practical Conference, May, 15–16, 2007, Vol. 2.* Saint-Petersburg-Pavlovsk: 282–290.

Rucins, A., A. Vilde, J. Nowak, 2007. Impact of the share inclination angle on the ploughing resistance. *TEKA Commission of Motorization and Power Industry in Agriculture, Volume VII.* Polish Academy of Sciences Branch in Lublin, Lublin, Poland: 199 – 209.

Vilde, A. 1999. Dynamics of the soil tillage machine operating parts and their elements. *Proceedings of the Latvia University of Agriculture*, *Vol.1 (295).* Jelgava, Latvia: 36-44.

Vilde, A. 2003. The impact of soil moisture and composition on its properties and energy consumption of tillage. *TEKA Commission of Motorization and Power Industry in Agriculture, Volume III.* Polish Academy of Sciences Branch in Lublin. Lublin, Poland: 249 – 255.

Vilde, A. 2004. Mechanical and mathematical foundations for modelling the dynamics of soil tillage machine operating parts. *TEKA Commission of Motorization and Power Industry in Agriculture, Volume IV.* Polish Academy of Sciences Branch in Lublin. Lublin, Poland: 228–236.

Vilde, A., A. Rucins, G. Sevostjanovs, 2007. Impact of Speed on the Soil Sliding Resistance. *International Conference "Technical and Technological Progress in Agriculture", No 12, 20–21 September 2007*. Raudondvaris, Lithuania: 34–38.