TRACTION EFFORTS OF THE WORKING BODY OF THE THREE-LAYER CULTIVATOR-FERTILIZER

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Abstract: *The necessity to accurately place the necessary quantity of nutrients relative to the root system of plants requires an intra-soil layer wise application of site-specific fertilizer doses to different depths. To ensure the full nutrition of plants throughout the growing season, a new technology for intrasoil site-specific three-layer application of mineral fertilizers and a cultivator-fertilizer for its implementation are proposed. The traction force of its working body is determined.*
Keywords: *mineral fertilizers, site-specific application, precision farming, tractive effort, wide-blade tillage.*

It is known that soil destruction under the influence of a wedge can occur both by detachment and by shearing (shear), depending on the ratio of the ultimate normal and tangential stresses of the soil, which in turn depend on its moisture and the state of turf grass in top soil layer [1-4]. The strength properties of the soil can be described with sufficient accuracy by the theory of Sh. Kulon and O. Mohr. In this case, for a specific case, the angle of the shift is specified, based on the Zvorykin-Mohr formula.

The soil's resistance to deformers as a whole completely describes the rational formula of V. Goryachkin, consisting of 3 members:

$$P = fG + \text{кав} + \xi\, \text{ав} V^2, \quad (1)$$

where: f, k, ξ – are the coefficients, G – is the weight of the plow; *a, b*– depth and width of treatment; V – is the forward velocity.

Later A.P. Osadchiy increased the number of components of the total resistance to 4, NA. Pechertsev, V.I. Vinogradov, G.A. Degraf - up to five, and RA. Martirosov - up to six, which took into account the resistance of the formation to lifting, cutting, compression, installation angle, the type of soil destruction, etc. However, G.N. Sineokov and I.M. Panov noted that theoretical formulas for determining the components of traction resistance, taking into account the deformations of the soil, were not found. Therefore, they believe that in each specific case the tractionresistance should be determined empirically [1].

The covering working body of the cultivator-fertilizer being developed is a double-winged share, such as a plain plow [5], figure 1. One wing AB is shown in Figure 2a.

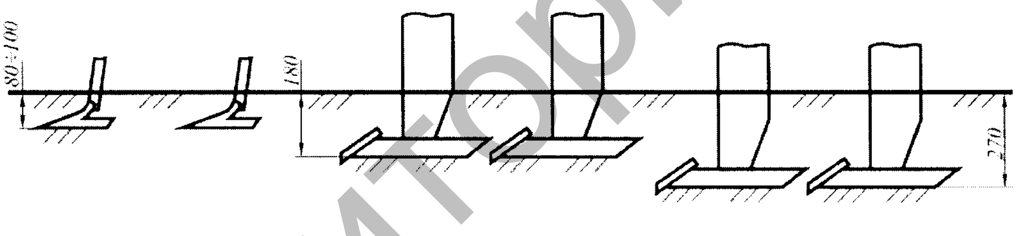
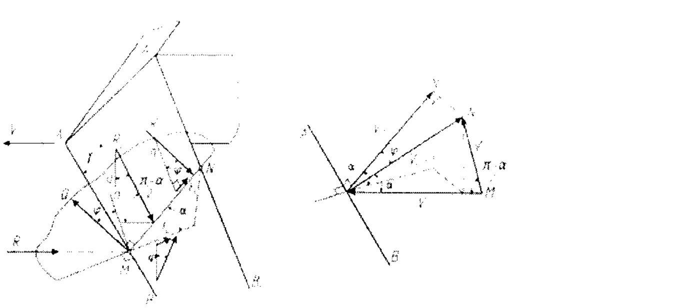


Figure 1 - Technological layout of the working arrangements of a three-layer cultivator-fertilizer

The working part moving in the soil at a speed *V* and acting on it with the force *Q*. It is the result of the action of the blade by a normal reaction and frictional forces. This, the active force is counteracted by the following resisting forces:

R_1 – the head support of the soil layer displaces the working body in it;
R_2 - the inertial forces of the soil, which it receives from the influence of the working body;
R_3 – oblique support of the formation on the face AA1 BB1;
R_4 – support of the bottom of the furrow;
F_3 – frictional forces on the face AA_1BB_1;
F_4 – forces of friction of the bottom of the furrow on the lower edge of the working body.



а) б)

Figure 2 - On the interaction of the covering working body with the soil

In figure 2, the *MN* line shows the direction of the largest slope and in the absence of frictional forces, the soil particles would move along it. In this case, the resisting forces R_3 and R_4 deviate from the normals n to the line *MN* by an angle φ in the direction opposite to the possible displacement of soil particles. And the inertial force R_2 also deviates to this side, not only from the normal n, but from the free fall line q.

The inertial forces R_2 appear at the initial moment of interaction of the working body with the soil, since at that time the inertia of the rest of the soil is disturbed, its particles acquire certain accelerations and some absolute velocity that do not coincide with the slope line *MN*. Obviously, the inertial force R_2 will be directed along the line of absolute velocity of particles, but only in the opposite direction.

A priori, it can be suggested that the soil particles will lag behind the surface of the working body with the same speed with which the working body will be introduced into the soil. Ideally, they are certainly not equal, because due to the crushing of soil particles and gas voids, the speed of the working element should be slightly higher than the speed of the soil. However, this difference, compared to their absolute values,is so small that they can be neglected.

In Fig. 2b, in the absence of frictional forces, the relative velocity will travel along the line $V_{\text{от}1}$. Due to frictional forces, the particle M will not move to point N after time t, but will move to point N_1. The relative velocity of the particle is equal to

$$V_{\text{от}2} = \frac{V_{\text{от}1}}{\cos\varphi} = V. \qquad (2)$$

According to the triangle rules of the speed, the relative speed is closed by absolute speed. In this case, from the sine theorem, we have:

$$\frac{V_a}{\sin M} = \frac{V_{\text{от}2}}{\sin M_0};$$

$$V_a = V_{\text{от}2}\frac{\sin M}{\sin M_0}. \qquad (3)$$

Define the angle M_0:

$$< M_0 = \pi - (< N_1 + < M)$$

As $V_{\text{от}2} = V$, $<N_1 = <M_0$. Consequently:

$$< M_0 = \pi - (< M_0 + < \alpha);$$

$$< 2M_0 = \pi - \alpha;$$

$$< M_0 = \frac{\pi - \alpha}{2}. \qquad (4)$$

Taking into account (2) and (4) from (3) we obtain:

$$V_a = V\frac{\sin\alpha}{\sin\frac{\pi-\alpha}{2}} = V\frac{\sin\alpha}{\cos\frac{\alpha}{2}}. \qquad (5)$$

The transformation (5) gives:

$$V_a = V\frac{2\sin\frac{\alpha}{2}\cos\frac{\alpha}{2}}{\cos\frac{\alpha}{2}} = V\,\mathrm{tg}\frac{\alpha}{2}. \qquad (6)$$

It follows from the last expression that the absolute velocity of the soil V_a is directed at an angle (π-α)/2 to the direction of the velocity of the working element and to the side opposite to the motion of the particles. Consequently, inertial forces are also directed along the line V_a in the opposite direction.

To determine the resistance of the soil environment to the working element of the cultivator-fertilizer we will compose the equations of equilibrium of all forces on the horizontal and vertical directions:

$$Q\cos\left[\frac{\pi}{2} - (\alpha + \varphi)\right] = R_2\cos\frac{\pi - \alpha}{2} + R_3\cos\left[\frac{\pi}{2} - (\alpha + \varphi)\right] + R_4\sin\varphi + R_1\frac{1}{\sin\gamma};$$

$$Q\sin\left[\frac{\pi}{2} - (\alpha + \varphi)\right] = R_2\sin\frac{\pi - \alpha}{2} + R_3\sin\left[\frac{\pi}{2} - (\alpha + \varphi)\right] + R_4\cos\varphi.$$

$$Q\sin(\alpha + \varphi) = R_2\sin\frac{\alpha}{2} + R_3\sin(\alpha + \varphi) + R_4\sin\varphi + R_1\frac{1}{\sin\gamma} = 0;$$

$$Q\cos(\alpha + \varphi) = R_2\cos\frac{\alpha}{2} + R_3\cos(\alpha + \varphi) + R_4\cos\varphi. \qquad (7)$$

The inertial forces in (7) can be expressed in terms of the acceleration and mass of soil particles:

$$R_2 = a \cdot m, \qquad (8)$$

where: a – acceleration of soil particles;

m – mass of deformable soil.

If we take the initial velocity of the particles equal to $V_0 = 0$, the finite velocity V_a and the transit time of the particles the width of the working member (L_l: V), then the required particle acceleration will be:

$$a = \frac{\Delta V}{\Delta t} = \frac{(V_a - V_0)V}{L_l};$$

We transform the last expression with allowance for (6):

$$a = \frac{V^2}{L_l}\cdot \mathrm{tg}\frac{\alpha}{2}. \qquad (9)$$

During the considered time, a soil layer with a mass will pass through the working body:

$$m = L \cdot H \cdot L_l\rho\sqrt{\frac{1}{1+tg^2\alpha}}, \qquad (10)$$

where: L – halfwidth of the sweep of the working body;

H – tillage depth:

ρ – bulk density of soil;

L_l – the path length of the particle along the working member (MN1).

Substituting (9) and (10) into (8) we obtain:

$$R_2 = L \cdot H \cdot \rho \cdot V^2\,\mathrm{tg}\frac{\alpha}{2}\cdot\sqrt{\frac{1}{1+tg^2\alpha}}. \qquad (11)$$

On the basis of the linear theory, the head support can be estimated by the transverse area of the undeformed formation in front of the working body:

$$R_1 = B \cdot H \cdot \sigma_{\text{сж}} = L\sin\gamma \cdot H \cdot \sigma_{\text{сж}}, \qquad (12)$$

where: B – halfwidth of the working body;

$\sigma_{\text{сж}}$ – ultimate soil crumpling resistance.

It can be determined from figure 1a:

$$R_3 = \frac{L_l \cdot H}{\cos\varphi}\cdot\sigma_{\text{сж}}; \qquad (13)$$

$$R_4 = \frac{L_H \cdot H}{\cos\varphi}\cdot\sigma_{\text{сж}}, \qquad (14)$$

where: $L_H = \mu L_l$ – width of the lower cut of the working member;

$\mu \approx 0{,}1 \div 0{,}2$ – coefficient that takes into account a part of the working width of the sweep.

$$\frac{R_1}{\cos\gamma} + R_3\cos\left[\frac{\pi}{2} - (\alpha+\varphi)\right] + R_4\sin\varphi = Q\cos\left[\frac{\pi}{2} - (\alpha+\varphi)\right] - R_2\cos\frac{\pi-\alpha}{2};$$
$$R_3\sin\left[\frac{\pi}{2} - (\alpha+\varphi)\right] + R_4\cos\varphi = Q\sin\left[\frac{\pi}{2} - (\alpha+\varphi)\right] - R_2\sin\frac{\pi-\alpha}{2}.$$

$$Q\sin(\alpha+\varphi) - R_2\sin\tfrac{\alpha}{2} = R_3\sin(\alpha+\varphi) + R_4\sin\varphi + \tfrac{R_1}{\cos\gamma}; \qquad (15)$$
$$Q\cos(\alpha+\varphi) - R_2\cos\frac{\alpha}{2} = R_3\cos(\alpha+\varphi) + R_4\cos\varphi.$$

Substituting (12), (13), and (14) into (15), we obtain:

$$Q\sin(\alpha+\varphi) - R_2\sin\frac{\alpha}{2} = \left[\frac{L_l\cdot H}{cos\varphi}\sin(\alpha+\varphi) + \frac{\mu L_l\cdot H}{cos\varphi}\sin\varphi + L\cdot H\,\mathrm{tg}\,\gamma\right]\cdot\sigma_{сж};$$

$$Q\cos(\alpha+\varphi) - R_2\cos\frac{\alpha}{2} = \left[\frac{L_l\cdot H}{cos\varphi}\cos(\alpha+\varphi) + \frac{\mu L_l\cdot H}{cos\varphi}\cos\varphi\right]\cdot\sigma_{сж}.$$

From the last system of equations, we determine the normal stresses of the soil crushing:

$$\sigma_{сж} = \frac{Q\sin(\alpha+\varphi) - R_2\sin\frac{\alpha}{2}}{\frac{L_l\cdot H}{cos\varphi}[\sin(\alpha+\varphi) + \mu\sin\varphi] + L\cdot H\,\mathrm{tg}\,\gamma};$$
$$\sigma_{сж} = \frac{Q\cos(\alpha+\varphi) - R_2\cos\frac{\alpha}{2}}{\frac{L_l\cdot H}{cos\varphi}[\cos(\alpha+\varphi) + \mu]}. \qquad (16)$$

Equate the right-hand sides of the equalities obtained:

$$\frac{Q\sin(\alpha+\varphi) - R_2\sin\frac{\alpha}{2}}{\sin(\alpha+\varphi) + \sin\varphi + LH\,\mathrm{tg}\,\gamma} = \frac{Q\cos(\alpha+\varphi) - R_2\cos\frac{\alpha}{2}}{\cos(\alpha+\varphi) + \mu}.$$

We transform the last equation:

$$Q\sin(\alpha+\varphi)\cdot\cos(\alpha+\varphi) + \mu Qsin(\alpha+\varphi) - R_2\sin\frac{\alpha}{2}\cos(\alpha+\varphi) - R_2\mu\sin\frac{\alpha}{2} =$$
$$= Q\cos(\alpha+\varphi)\sin(\alpha+\varphi + Q\cos(\alpha+\varphi)\sin\varphi + Q\cos(\alpha+\varphi)\cdot LH\,\mathrm{tg}\,\gamma - R_2\cos\frac{\alpha}{2}\sin(\alpha+\varphi) - R_2\cos\frac{\alpha}{2}$$
$$\cdot\sin\varphi - R_2\cos\frac{\alpha}{2}LH\,\mathrm{tg}\,\gamma;$$
$$Q[\mu\sin(\alpha+\varphi) - \cos(\alpha+\varphi)] - Q\cos(\alpha+\varphi)\,LH\,\mathrm{tg}\,\gamma =$$
$$R_2\left[\sin\tfrac{\alpha}{2}(\cos(\alpha+\varphi)+\mu) - \cos\tfrac{\alpha}{2}(\sin(\alpha+\varphi)+\sin\varphi)\right] - R_2LH\,\mathrm{tg}\,\gamma\cos\tfrac{\alpha}{2}. (17)$$

We accept the notation:

$$\mu\sin(\alpha+\varphi) - \cos(\alpha+\varphi) = A_1;$$
$$\cos(\alpha+\varphi) = A_2; \qquad (18)$$
$$\sin\frac{\alpha}{2}[\cos(\alpha+\varphi)+\mu] - \cos\frac{\alpha}{2}[\sin(\alpha+\varphi)+\sin\varphi] = B_1.$$
$$\cos\tfrac{\alpha}{2} = B_2.$$

Parameters included in A_1, A_2 and B_1, B_2 for a specific working body are constant. Therefore, for a given tool, they can be considered as constant quantities. In this case, the presentation of the final formula, their calculation and analysis are simplified.

Substituting the notation in (17), we obtain:

$$QA_1 - QA_2\,LH\,\mathrm{tg}\,\gamma = R_2B_1 - R_2B_2LH\,\mathrm{tg}\,\gamma;$$

$$Q(A_1 - A_2\,LH\,\mathrm{tg}\,\gamma) = R_2(B_1 - B_2LH\,\mathrm{tg}\,\gamma);$$

$$Q = \tfrac{(B_1 - B_2LH\,\mathrm{tg}\,\gamma)}{(A_1 - A_2LH\,\mathrm{tg}\,\gamma)}. \quad (19)$$

Taking into account (11) and referring to the second half of the body paw, from (19) we have:

$$Q = 2LH\rho V^2\,\mathrm{tg}\tfrac{\alpha}{2}\sqrt{\tfrac{1}{1+\mathrm{tg}^2\alpha}} - \tfrac{(B_1 - B_2LH\,\mathrm{tg}\,\gamma)}{(A_1 - A_2\,LH\,\mathrm{tg}\,\gamma)}. \quad (20)$$

Analysis of Eq. (20) shows the direct dependence of the tractive effort on the width of the tillage of the tillage and the depth of treatment and the quadratic dependence on the speed of the cultivator-fertilizer, Fig. 3, 4.

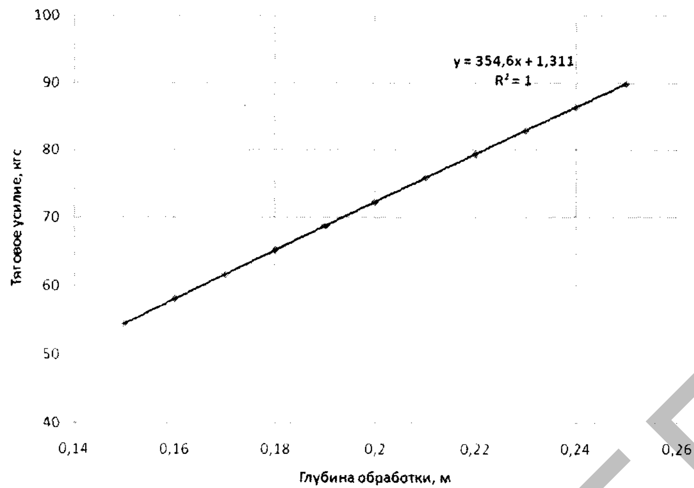


Figure 3 - Traction force versus treatment depth

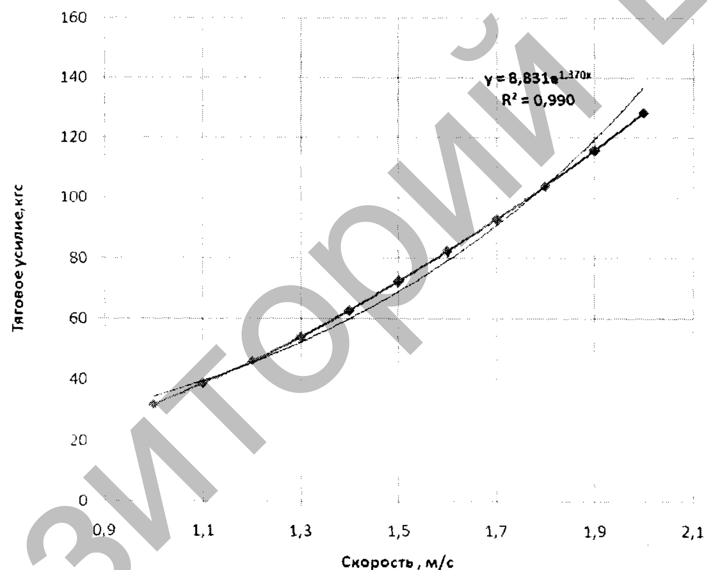


Figure 4 - Traction force versus speed

Increasing the depth of processing from 15 cm to 25 cm and the rake angle of the ploughshare from 15 to 25 degrees increases tractive effort by 40-50%, and increasing the sweep angle in the range from 55 to 65 degrees has a negligible effect on tractive effort, Fig. 5.

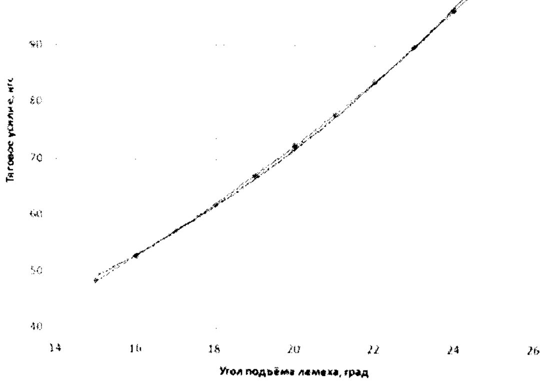


Figure 5 - Dependence of tractive effort on the rake angle ploughshare

For an approximate calculation of the tractive effort of one working body, we take the initial data:
$2L = 0,5$ м - length of share of paws;
$H = 0,2$ м - processing depth;
$\rho = 10^3$кг/м^3 - soildensity;
$\alpha = 20°$ - rake angle;
$\gamma = 60°$ - sweep angle;
$\mu = 0,1$ - the ratio of the lower and upper cuts edge of the share;
$\varphi = 30°$ - angle of friction.

$$Q = 2 \cdot 0,25 \cdot 0,2 \cdot 10^3 \cdot 2,2 \cdot 0,17 \sqrt{\frac{1}{1+0,132} \cdot \frac{(-1,117) - 0,984 \cdot 0,25 \cdot 0,2 \cdot 1,732}{(-0,566) - 0,642 \cdot 0,25 \cdot 0,2 \cdot 1,732}} = 70,53 кгс$$

$A_1 = 0,1 \cdot 0.76 - 0,64 = -0,566;$
$A_2 = 0,642;$
$B_1 = 0,17[0,64 + 0,1] - 0,98[0,76 + 0,5] = 0,125 - 1,234 = -1,117$
$B_2 = 0,984.$

The calculation shows the expected result. A further research program will include laboratory-field experimental testing.

Acknowledgements The authors express their gratitude to the Ministry of Education and Science of the Republic of Kazakhstan for the funding research works on the topic №5057/ГФ4 "Development of new technology and equipment for the three-layer subsurface site-specific application of mineral fertilizers". The current theoretical study was carried out within this topic.

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