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Theoretical Justification of Optimal Geometric and Kinematic Parameters in Moving Parts of Clod-Crusher in Potato Harvester

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ABSTRACT

The impact of geometric forms and sizes of the working parts in the automated clod crusher of the potato harvester on the soil-sticking and motion resistance force, as well as on the clods strike and their throwing velocity have been studied. Theoretic investigations have resulted in the derivation of expressions which enable to determine the resistance force and the clods throwing velocity for cylindrical flat-fronted, cylindrical hemispheric-fronted and conical headed clod crushers.

It has been disclosed that the form of the crusher's working part practically has zero impact on the soil clods throwing velocity; it is a constant value for all considered cases.

Introduction

The study of dynamics of interaction between soil and moving parts of tillage machines (ploughs, cultivators, trench digger) is hitherto an actual issue. Though there are numerous researches (Goryachkin, 1968, Sineokov, Panov, 1977, Tarverdyan, 2014) in this area their theoretical and empiric investigations on designing new soil cultivation machines are insufficient to accurately determine their optimal geometric, kinematic and dynamic parameters. The difficulty in solving the problem is also related to great diversity and variability of the physical-mechanical properties of the soil (ground) in one and the same field.

It is approved that the resistance force p of solid body's (tillage machine working part) sticking motion into the soil can be introduced as a sum of three forces (Goryachkin, 1968, Sineokov, Panov, 1977, Tsytovich, 1983, Tsvetkova, 2004).

$$P = P_1 + P_2 + P_3$$

Where P_1 is the dynamic force resulted from the inertia of the environmental particles. It is assumed that it is directly proportional to the motion velocity square of the moving part v^2. P_2 is the force of environmental viscosity that appears due to overcoming contact forces between the environmental particles and the moving machine part. It is directly proportional to its motion speed V. P_3 is the force of the environmental static resistance, the value of which does not depend on speed, but is determined by the soil strength index.

Thus, P force can be represented as follows:

$$P = Av^2 + Bv + C$$

Where A, B and C are positive constants and the values of which depend on the soil properties and the form and size of the working part.

From that standpoint the issue related to determining the optimal values of the geometrical and kinematic parameters of clod crusher in the potato harvester becomes very urgent.

Materials and methods

Three finger types have been designed for the recommended clod crusher: flat-fronted cylindrical, cylindrical hemispheric-fronted and conical (Tarverdyan, Yesoyan, et. al, 2019). (figure 1):

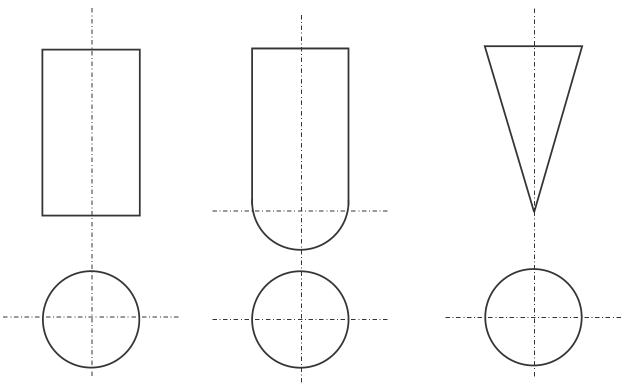

Figure 1. The diagram of experimental fingers of clod crusher in potato harvester.

Testing of different types of crushing fingers is conditioned by the need for the choice of the best option in case of which, the maximum possible clod grinding sizes will entail to the minimum value of traction resistance.

Let's discuss nominated options individually, and then compare the results per sticking force resistance in clod grinding. We will also estimate the perfection of the proposed theory and its application in the design and calculation of other soil tilling machines by comparing theoretical research and experimental results.

Results and discussions

1. Flat-fronted cylindrical crusher.

Obviously, in case of theoretical solution of the problem, first, it is necessary to make assumptions and form a design model. Let's admit that the crusher is an absolutely rigid cylinder with V_0 speed that is vertical to the cylinder axis and strikes into the plane of the soil semi-space. Let's determine the regularity of cylinder's sticking into the soil environment, the latter being a plastic compressible environment.

The experiments have shown that after striking the soil environment is subjected to the wave movement within the volume of semi-space at the striking surface of cylinder, the rest of soil volume practically remains unused (Tsytovich, 1983, Tsvetkova, 2004, Tarverdyan, Khanaghyan, 2016, Knaus, 1968). It is assumed that the striking speed is high and the tangent forces of cylindrical surface can be ignored especially when those forces do not play any particular role in the crushing process.

Upon these assumptions, a flat shock wave spreads from the striking point in soil due to which particles are always in smooth one-dimensional movement. The motion of the soil (clod) between the sticking cylindrical surface and the shock wave is described through the following equation (Tsytovich, 1983, Tsvetkova, 2004, Tarverdyan, Khanaghyan, 2016, Loitsanski, Lurie, 2006):

$$\rho\left(\frac{\partial v}{dt}+v\frac{dv}{dx}\right)=-\frac{\partial p}{dx}\ , \qquad (1)$$

where x is the coordinate that derives from the point of intersection of the axis of the cylinder surface and the plane of the ground (Figure 2);

ρ - the density of the clod

p - the pressure in the cylinder and soil interaction zone

v- the speed of the cylinder front section (or soil particles).

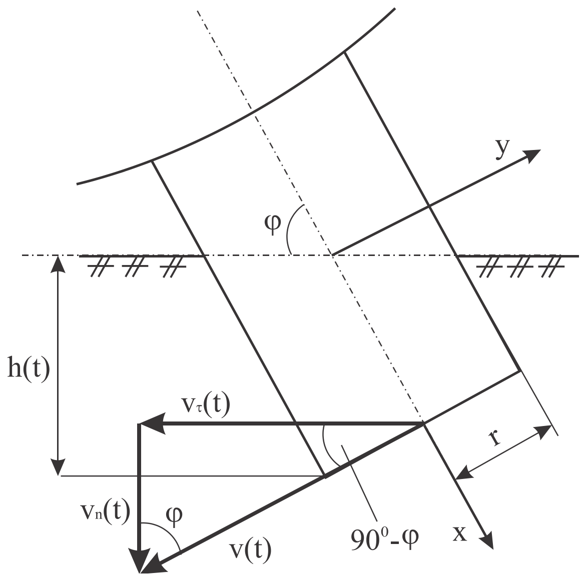

Figure. 2. The diagram of sticking cylindrical clod-crusher *(composed by the authors).*

As we have noted, the soil is accepted as a plastic compressible environment the density of which changes only on the shock wave. The density beyond the wave is the same for all the particles.

It is confirmed that such an assumption enables to get possibly simple expressions without significant distortion of the final results (Tsitovich, 1983, Tsvetkova, 2004, Vinogradov, 1968).

Due to condition of incompressibility it follows that $\frac{dv}{dx}=0$, therefore the velocity of soil particles is only a time function t: If $h(t)$ is the sticking depth of crusher then:

$$v_n(t)=\dot{h} \qquad \frac{\partial v_n(t)}{\partial t}=\ddot{h}\,, \tag{2}$$

where $v_n(t)=v(t)\cos\varphi$ is the vertical component of speed, φ -the angle of the cylinder axis and the soil surface plane, which changes in $\varphi_0 \div \frac{\pi}{2}$ domain during the rotation of the crusher device and φ_0 is a constructive parameter.

In case of the proposed device: $\varphi_0=45°$.

Thus, expression (1) can be presented as follows:

$$\rho\ddot{h}=-\frac{dp}{\partial x}\,. \tag{3}$$

By integrating, we get the following according to X:

$$p=-\rho\ddot{h}x+c. \tag{4}$$

On the shock wave at the level of $x=h_1$ coordinate we will have the following for pressure:

$$p_i=-\rho\ddot{h}h_i+c\,. \tag{5}$$

On the other hand, the following expressions are derived from the basic laws of motion mechanics on the shock wave (Knaus, 1968, Loitsanski, Lurie, 2006):

$$p_i=\frac{\rho_0\left(\dot{h}\right)^2}{1-k}, \qquad h_i=\frac{h}{1-k} \qquad k=\frac{\rho_0}{\rho}, \tag{6}$$

ρ_0 is the preliminary soil density before the movement. For the section of frontal cylindrical crusher $x=h$, therefore the expression will look like the following :

$$p=-\rho\ddot{h}h+C. \tag{7}$$

Eliminating integration C constant from (5) and (7) we will have:

$$p=p_i+\rho\ddot{h}\left(h_i-h\right). \tag{8}$$

Using (6) expressions we will get following expression for (8):

$$p=\frac{\rho_0}{1-k}\left[\left(\dot{h}\right)^2+\ddot{h}h\right]. \tag{9}$$

The force acting by the soil environment on frontal surface of cylindrical crusher with absolute value will be:

$$P=\frac{A\rho_0}{1-k}\left[\left(\dot{h}\right)^2+\ddot{h}h\right]. \tag{10}$$

Where A is the front surface area of the clod crusher. In the considered case it is a circle, therefore:

$$P=\frac{\pi r^2\rho_0}{1-k}\left[\left(\dot{h}\right)^2+\ddot{h}h\right]. \tag{11}$$

Usually the second member of the bracket expression is smaller than the first one, so it can be ignored in practical calculations. To effectively break and loosen the clods it is necessary to determine the minimal speed limit in the strike. Let's assign the mass of the working part as M. In this case, we can introduce the equation of motion and crusher sticking into the soil environment as follows:

$$M\ddot{h}=-\frac{\pi r^2\rho_0}{1-k}\left(\dot{h}\right)^2. \tag{12}$$

This equation is brought into the first-degree equation that is easily integrated. As a result we will get:

$$\dot{h}=v_0e^{-\frac{\lambda h}{M}}, \quad h=\frac{M}{\lambda}l_n\left(1+\frac{\lambda v_0}{M}t\right), \tag{13}$$

where $\lambda=\frac{\rho_0\pi r^2}{1-k}$:

Since $\dot{h}=v_n(t)$, for the clods' throwing speed $v_\tau(t)$ we will have (Figure 2):

$$v_\tau(t)=v_0tg\phi e^{-\frac{\lambda h}{M}}.$$

The last obtained and (13) expressions allow determining both the striking force and the velocity of particles.

2. Consider the motion regularity and sticking of the working part (crusher) into soil when the corpus of the part is cylindrical and the front part is hemisphere (Figure 3). It should be noted that all the above mentioned hypotheses and assumptions concerning the environment are also used in this case.

Considering the plastic nature of the soil environment deformation, the shock wave in the soil will be very close to the hemisphere surface, consequently the pressure on the latter can be determined through the following expression with some approximation (Tsytovich, 1983, Tsvetkova, 2004, Vinogradov, Semenov, 1968):

$$p=\left(1-\frac{k}{2}\right)\rho_0v_n\cos^2\theta \tag{14}$$

where $v_n=v\cos\varphi$ - is the vertical component of velocity $k=\frac{\rho_0}{\rho}$, the compressibility level of clod, θ is the current angle composed of the radius of current observed A point of hemisphere and sticking direction:

$$-\frac{\pi}{2} \le \theta \le \frac{\pi}{2}.$$

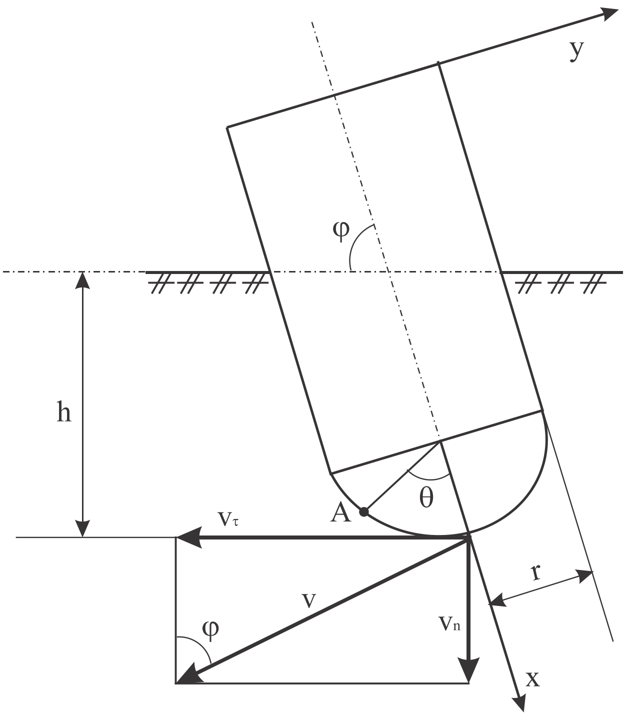

Figure 3. Diagram of clod crusher with hemisphere front *(composed by the authors).*

Consider the sticking case of the crusher when $h < r$. In this case, the current angle θ will be determined by the following expression:

$$\cos\theta = \frac{r-h}{r}. \quad (15)$$

The force of sticking resistance of hemisphere at that moment will be:

$$P = \int_0^\theta pds, \quad (16)$$

where $ds = 2r2\sin\theta d\theta$ is the area of the sticking part of the hemisphere surface. By placing the value of the pressure p from the expression (14) and then integrating it, we will have:

$$P = \frac{1}{2}\rho_0 v_n \pi r^2 \left(1-\frac{k}{2}\right)\left(1-\cos^4\theta\right). \quad (17)$$

Taking into account the (15) expression, the (17) one can be presented as follows:

$$P = \frac{1}{2}\rho_0 v_n^2 \pi r^2 \left(1-\frac{k}{2}\right)\left[1-\left(1-\frac{h}{r}\right)^4\right]. \quad (18)$$

During the crusher's further sticking process $h \ge r$ additional pressure affects the frontal hemisphere surface. We obtain the absolute value of the resistance force (18) from the expression assuming that $h = r$:

$$P = \frac{1}{2}\rho_0 v^2 \pi r^2 \left(1-\frac{k}{2}\right). \quad (19)$$

To determine the velocity of the particles of clod we use Newton's second law:

$$\frac{2M}{\pi r^2 \rho_0 \left(1-\frac{k}{2}\right)v}\frac{dv}{dh} = -1 + \left(1-\frac{h}{r}\right)^4, \quad (20)$$

where M is the mass conveyed by the crusher.

By integrating this expression from initial values $v=v_0$, $h=0$ up to their current values during the sticking process we'll have:

$$\frac{2M}{\pi r^2 \rho_0 \left(1-\frac{k}{2}\right)}\ln\frac{v}{v_0} = h + \frac{r}{5}\left[1-\left(1-\frac{h}{r}\right)^5\right]. \quad (21)$$

In case of h=r, the velocity of particles (21) will be:

$$v = v_0 e^{-\frac{8M}{5\pi r^2 \rho_0 \left(1-\frac{k}{2}\right)}}. \quad (22)$$

The throwing speed of clods (figure 3) will be:

$$v_\tau = v_0 tg\phi e^{-\frac{8M}{5\pi r^2 \rho_0 \left(1-\frac{k}{2}\right)}}.$$

3. Let's consider the last of the three versions of the clod crushers, that is the sticking and moving regularities of the crusher with conical head in the clod mass.

Let us assume that the crusher with conical head and cylindrical corpus confronts the soil surface and is stuck into it with initial speed v. The cone generator with the soil surface forms β angle, hence the contact surface of conical crusher and clod gets wider with $v_A = v\,ctg\beta$ velocity.

In order to simplify the solution of the task let us make an extra assumption by moving the marginal terms from the surface of the cone body to the horizontal projection of the contact surface (through the comparison of further theoretical and empiric results it will be further shown that this assumption does not have any significant impact). After that, the conical body and the soil contact area will come forth as a disk surface with *r(t)* radius. Moreover, the *r(t)* radius increases with $v\,ctg\beta$ speed and the disk points generate a smooth one-dimensional motion of the soil particles in the soil plastic compressing environment with *r(t)* velocity vertically down to the bottom.

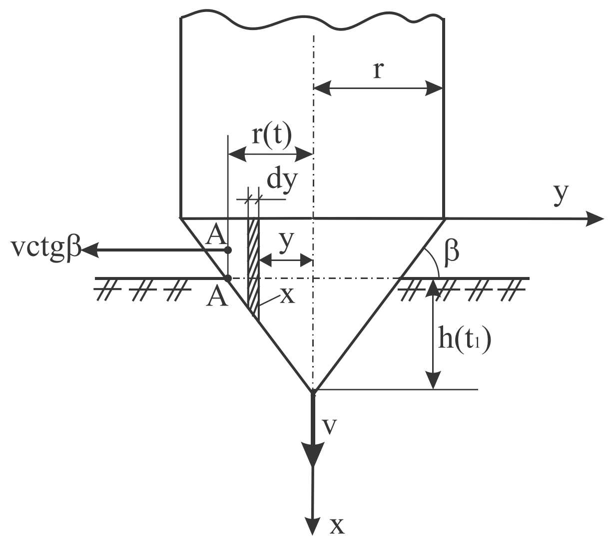

Figure 4. The diagram of the sticking clod crusher with conical head (*composed by the authors*).

In case of equable smooth motion of the soil particles, the environmental pressure affecting the conical surface as of expression will be:

$$p = \frac{\rho_0}{1-k}\left(v(t)^2 + \dot{v}(t)\,x \right), \qquad (23)$$

where $v(t)$ is the sticking velocity at the *t* moment, *x* is the sticking size of the mentioned disk point at that moment. Let's assume that the particle which is in y distance from disk axis starts the motion at the moment of t_1. In that case we'll have:

$$y = \int_0^{t_1} v\,ctg\beta\, dt_1 = h(t_1)\,ctg\beta, \qquad (24)$$

where $h(t_1)$ is the sticking depth of cone head at $t_1 < t$ moment.

The depth of the sticking point $x(t;\, t_1)$ located in y distance from disk center will be determined through the following expression:

$$x(t;\, t_1) = \int_{t_1}^{t} v(t)\,dt = h(t) - h(t_1). \qquad (25)$$

The force of the soil environment impact on conical surface will be determined by the following expression:

$$P = \int_0^{h(t)ctg\beta} p\,2\pi y\,dy\,,$$

or taking into account the expressions (23), (24) and (25):

$$P = \frac{2\pi\rho_0 ctg^2\beta}{1-k} \cdot$$

$$\cdot \left\{ v^2(t)\int_0^t h\dot{h}\,dt_1 - \dot{v}(t)\int_0^t \left[h(t) - h(t_1) \right] \dot{h}(t_1)\,h(t_1)\,dt_1 \right\}. \qquad (26)$$

After calculating the integrals, the expression of *P* force will look as follows:

$$P = \frac{\pi\rho_0 ctg^2\beta}{1-k}\left\{ v^2h^2 - \dot{v}(t)\frac{h^3}{3} \right\}. \qquad (27)$$

As in the previous two cases, we use Newton's second law to determine the sticking regularity:

$$M\frac{dv}{dt} = -\frac{\pi\rho_0 ctg^2\beta}{1-k}\left\{ v^2h^2 - \frac{h^3}{3}\frac{dv}{dt} \right\}. \qquad (28)$$

The last expression will be presented in the following form:

$$\frac{M}{v}\frac{dv}{dt} = -\frac{ah^2}{1+\dfrac{ah^3}{3M}}\,, \qquad (29)$$

where the following was assigned: $\alpha = \dfrac{\pi\rho_0 ctg^2\beta}{1-k}$.

The second member of the denominator at the right part of the expression (29) is much smaller than the first one. Thus, ignoring it we can write:

$$\frac{M}{v}\frac{dv}{dt} = -ah^2,$$

whereupon, taking into account the marginal values of velocity we will get the following for the velocity of particles:

$$v = v_0 e^{-\frac{ah^3}{3M}}. \qquad (30)$$

It should be noted that, like in the previous two cases, the crusher fingers get stuck into the variable φ angle of axis slant. In this case, for the throwing velocity in the tangent direction of clods we will have:

$$v_\tau = v_0 tg\phi e^{-\frac{\pi\rho_0 h^3 ctg^2\beta}{3M(1-k)}}.$$

Thus, in the three discussed cases we obtained expressions for the crusher's working part sticking and motion resistance force in the soil, as well as the clods' throwing velocities.

Taking into account the main geometrical and kinematic parameters of the testing machine, theoretical values of throwing velocity in clods and sticking resistance force of the moving part is presented below.

Baseline data: technological speed of potato harvester- 1.2 m/s the radius of moving tire - 0.2 m, crusher's rotor rotation frequency - $\omega_1 = 4.88\ s^{-1}$, the transfer number of planetary gear - 8.2, the average rotation radius of crusher's working part - $R_2=0.18\ m$, rotation frequency- 39.04 s^{-1}, the circular velocity of the working part *7.027 m/s, k= 0.40-0.75, r=* 0.015 m, $\rho_0 = 1200\ kg/m^3$, *M=0.45 kg*, $\varphi=60^0$ (for intermediate position).

1. In case of a cylindrical flat- fronted crusher
   P=24.34 N, $v_\tau = 9.76\ m/s$.
2. In case of a cylindrical hemispheric- fronted crusher
   P=15.03 N, $v_\tau = 9.73\ m/s$.
3. In case of conical head crusher
   P=8.91 N, $v_\tau = 9.63\ m/s$.

Conclusion

The geometrical form of the clod crusher's working part of potato harvester does not affect the throwing velocity of clods and is constant in conditions of identifiable kinematic parameters. While the sticking and clod crushing resistance force of the working part changes considerably; the minimum value is achieved in case of conical head crusher.

Thus, the resistance force should be taken as a key indicator in the choice of optimal geometric forms and sizes for the clod crusher. As for more generalized conclusions the results of field experiments of the proposed options are needed.

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