International
Journal
Of Advanced Research in Engineering & Management (IJAREM)
ISSN: 2456-2033 || PP. 37-42

Description of the Soil Crushing Process using a Toothed Working Tool

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Abstract: Objective: Ukraine's chernozems represent one of the nation's most valuable assets and a strategic resource. The quality and fertility of soils significantly depend on the processing method and the structural features of the processing tool. To intensify the process, improve quality, and reduce energy consumption in soil processing, a design of a toothed working tool (TWT) has been proposed. The task is to test the effectiveness of the new TWT, investigate the mechanics of soil crushingwhile processing it with a toothed working tool, and develop models for the interaction of soil with the tooth surfaces of the working tool.

Research Methods: Mathematical models of soil fragmentation mechanics while tilled with the toothed working tool have been developed. The crushing process consists of two sequential phases. In the first phase, the soil layer is disrupted as it passes through the frontal surface of the tool, designed in a logarithmic spiral. The disruption of the soil layer in the first phase depends on the machine's speed and the characteristic angle of the logarithmic spiral on the frontal surface of the TWT. Then, the layer is crushed on the undulating surface of a sinusoidal cylinder. After fragmentation on the frontal surface of the TWT, the soil enters the undulating surface already significantly loosened. During this phase, the layer undergoes deformation on the sinusoidal surface, further disrupting the integrity and pulverizing the soil layer through successive stretching (rupture) and compression deformations induced by the depressions and protrusions of the sinusoidal surface of the TWT. The combination of the spiral and sinusoidal surfaces of the toothed working tool ensures high-quality and energy-efficient soil processing.

Scientific Novelty: Considering modern agricultural realities and the prospects of Ukraine, soil processing with a new toothed tool featuring combined working surfaces in the form of a logarithmic spiral and a sinusoidal cylinder represents a timely, relevant, and novel direction in agricultural science.

Practical Value: Soil layer disruption during tillage with conventional working tools primarily occurs due to tensile deformations with shear. When processed with the proposed toothed working tool, additional compression, stretching, and bending stresses are generated in the soil due to the replication of the complex profile of the TWT's working surface. The non-uniform deformation field contributes to high-quality soil crushing during tillage with minimal energy consumption.

Keywords: Tillage, toothed working tool (TWT), logarithmic spiral, frontal surface, undulating surface, sinusoidal cylinder.

Quality of soil processing and energy consumption during the process depend significantly on the type of working tool. To intensify the process, enhance the quality, and reduce energy consumption during tillage, a design of a toothed working tool (TWT) is proposed and detailed in study [1]. In the proposed TWT, the frontal surface is constructed in a logarithmic spiral, followed by an undulating surface. The soil crushing processes on these surfaces during TWT cutting are different.

Let us consider the first phase of the process – the movement of the soil layer along the frontal surface of the TWT, which is constructed in a logarithmic spiral:

$$r_i = r_0 \cdot e^{\alpha * tg\varphi},$$

Where α is the current angle of the logarithmic spiral, rad;
φ is the angle of internal friction of the soil, rad.

The spiral surface of the tool is built considering the physical-mechanical properties of the soil and the depth of its tillage.

The disruption of the soil layer by the working tool occurs under the condition

$$N \geq [N_\partial]$$

Where $[N_\partial]$ is the ultimate force of normal soil pressure on the tool's working surface, N.

Cracks corresponding to rupture deformation are formed in the areas of concentration of the ultimate normal reaction of the soil.

To determine the normal component of the soil reaction, a diagram (Fig. 1) is used.

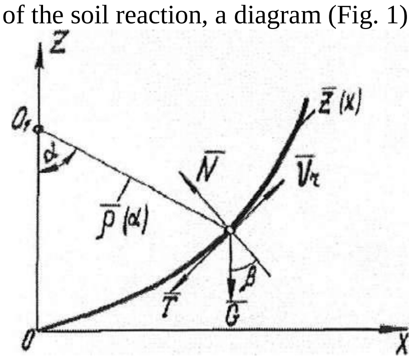

Figure 1 Scheme of soil movement along the front surface of the working tool

The movement of soil elements upward along the front surface of the TWT can be modelled as the motion of material points on a rough surface [2]. To determine the relative velocity of soil movement, we formulate the equation of equilibrium in the natural coordinate system using D'Alembert's principle

$$\left.\begin{aligned} m\frac{d\upsilon_r}{dt} &= -T - G\sin(\alpha-\beta) \\ N &= G\cos(\alpha-\beta) + m\frac{\upsilon_r^2}{\rho(\alpha)} \end{aligned}\right\}, \quad (1)$$

Where *m* is the mass of the soil located on the front surface and is determined by

$m = \gamma \cdot V$, kg;

V is soil volume, m^3;

γ is soil density, kg/m^3;

$T = fN$ – friction force of the soil on the tool, kN;

f is coefficient of friction of the soil on steel

$\rho(\alpha)$ is the radius of curvature of the working surface of the TWT, m;

υ_r is the speed of soil sliding over the working surface, m/s.

Let us determine the relative speed of the soil layer movement from equation (1).

$$m\frac{d\upsilon_r}{dt} = \left[mg\cos(\alpha-\beta) + \frac{m\upsilon_r^2}{\rho(\alpha)}\right]f - mg\sin(\alpha-\beta). \quad (2)$$

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Substituting $dt = \dfrac{\rho(\alpha)d\alpha}{\upsilon_r}$ and denoting $\upsilon_r^2 = y$, we obtain the equation

$$\frac{dy}{d\alpha} + 2yf = 2g\rho(\alpha)\left[f\cos(\alpha-\beta) + \sin(\alpha+\beta)\right]. \tag{3}$$

Integrate the equation with initial conditions α=0 and $\upsilon_r=\upsilon$, where υ is the speed of the working tool, m/s. Denoting the right-hand side of equation (3) as $\Phi(\alpha)$, we obtain the equation

$$\frac{dy}{d\alpha} + 2yf = \Phi(\alpha) \tag{4}$$

Which is a linear non-uniform equation that is solved by the method of arbitrary constants

$$y' + 2fy = 0; y = ce^{2f\alpha},$$

Where $c = c(\alpha)$ is an arbitrary constant.
Further transformations

$$y' = c'e^{-2f\alpha} - 2fce^{-2f\alpha}$$

Allow obtaining a convenient equation

$$\frac{dc}{d\alpha}\cdot e^{-2f\alpha} = 2g\rho(\alpha)\left[f\cos(\alpha-\beta) = \sin(\alpha-\beta)\right].$$

Therefore

$$c = 2g\int \rho(\alpha)e^{-2f\alpha}\left[f\cos(\alpha-\beta) + \sin(\alpha-\beta)\right]d\alpha, \tag{5}$$

Where $\rho(\alpha) = a\cdot e^{k\cdot\alpha}$ is a logarithmic spiral.

After substituting in the equation (5), we have

$$c = 2ga\left\{f\frac{e^{k+2f}}{(k+2f)^2+1}\begin{bmatrix}\cos(\alpha-\beta)(k+2f-1)+ \\ +\sin(\alpha-\beta)(\frac{k}{f}+3)\end{bmatrix}\right\} + c_1,$$

Where $k = tg\varphi$ is the coefficient of internal friction of the soil.

Given the initial conditions are $c(0) = \upsilon_m^2$, where υ_m is the speed of the machine, we get

$$\upsilon_m^2 = c_1 + 2ga\left\{\frac{fe^{k+2f}}{(k+2f)^2+1}\begin{bmatrix}\cos\beta(k+2f-1)- \\ -\sin\beta\left(\frac{k}{f}+3\right)\end{bmatrix}\right\};$$

$$c_1 = \upsilon_m^2 + 2ga\left\{\frac{fe^{k+2f}}{(k+2f)^2+1}\begin{bmatrix}\left(\frac{k}{f}+3\right)\sin\beta- \\ -(k+2f-1)\cos\beta\end{bmatrix}\right\}.$$

Thereafter

$$c(\alpha) = \upsilon_m^2 + 2ga\frac{fe^{k+2f}}{(k+2f)^2+1} *$$
$$* \begin{bmatrix} \left(\frac{k}{f}+3\right)\sin\beta + \\ + \sin(\alpha-\beta) - (k+2f-1)\cos\beta - \cos(\alpha-\beta) \end{bmatrix}.$$

After transformation, we have

$$y = \upsilon_r^2 = \begin{Bmatrix} \upsilon_m^2 + 4ga\frac{fe^{k+2f}}{(k+2f)^2+1}\sin\frac{\alpha}{2}\times \\ \times \begin{bmatrix} \left(\frac{k}{f}+3\right)\cos\left(\beta-\frac{\alpha}{2}\right) + \\ + (k+2f-1)\sin\left(\beta-\frac{\alpha}{2}\right) \end{bmatrix} \end{Bmatrix} e^{-2f\alpha}.$$

By entering the designations

$$4ga\frac{fe^{k+2f}}{(k+2f)^2+1} = A; \qquad \frac{k}{f}+3 = B;$$
$$(k+2f-1) = D,$$

We finally get

$$\upsilon_r = e^{-f\alpha}\sqrt{V_m^2 + A\sin\frac{\alpha}{\beta}\begin{bmatrix} B\cos\left(\beta-\frac{\alpha}{2}\right) + \\ + D\sin\left(\beta-\frac{\alpha}{2}\right) \end{bmatrix}}. \tag{6}$$

The equation (6) allows analyzing the dependence of soil sliding speeds along the frontal surface of the TWT at different points on the speed of the machine (υ_m) and the angle (α), determining the trajectory of the soil layer movement.

Substituting the value ofυ_r into equation (1) we determine N(α).In doing so, consider that G is the weight of the soil layer located on the working tool and depends on the established tillage depth

$$N(\alpha) = mg\cos(\alpha-\beta) + \frac{me^{-f\alpha}\left(V_m^2 + A\sin\frac{\alpha}{2}\begin{bmatrix} B\cos\left(\beta-\frac{\alpha}{2}\right) + \\ + D\sin\left(\beta-\frac{\alpha}{2}\right) \end{bmatrix}\right)}{ae^{k\alpha}};$$

$$N(\alpha) = m\left\{\frac{g\cos(\alpha-\beta)\cdot ae^{k\alpha} + e^{-f\alpha}\left(\begin{matrix} V_m^2 + A\sin\frac{\alpha}{2}\times \\ \times\left[B\cos\left(\beta-\frac{\alpha}{2}\right) + D\sin\left(\beta-\frac{\alpha}{2}\right)\right] \end{matrix}\right)}{ae^{k\alpha}}\right\}. \tag{7}$$

The disruption condition of a layer moving along the logarithmic spiral of the frontal surface of the TWT can be expressed by the following equation

$$m\left\{\frac{g\cos(\alpha-\beta)+e^{-f\alpha}\left(\begin{matrix}V_m^2+A\sin\dfrac{\alpha}{2}\times \\ \times\left[B\cos\left(\beta-\dfrac{\alpha}{2}\right)+D\sin\left(\beta-\dfrac{\beta}{2}\right)\right]\end{matrix}\right)}{ae^{k\alpha}}\right\}\geq\left[N_g\right] \tag{8}$$

In other words, the disruption of the soil layer in the first phase of the process depends entirely on the angle β, which characterises the logarithmic spiral of the tool's frontal surface.

Now consider the second phase of the process – the movement of the soil layer along the undulating surface of the TWT.

After the soil is crushed on the frontal surface of the TWT, the soil falls on the undulating surface already significantly loosened. Therefore, the movement of the crushed elements along this surface can be considered analogous to the movement of particles of a bulk material along the surface of a sinusoidal cylinder [3].

To consider the deformation and fragmentation of the soil in the second phase of the process, we will use the diagram (Fig. 2).

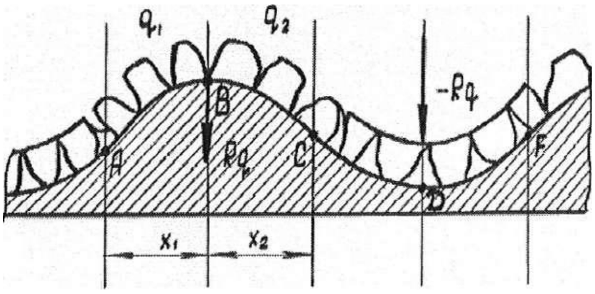

Figure 2 Scheme of the movement of the soil layer along the undulating surface of the TWT

At points *A*, *C*, *F*, bending results in stresses that tend to crush the layer. These points are the points of inflection of the layer on the sinusoidal surface. Here, the soil layer is crushed by bending deformations. In the AC section, the layer is disrupted by fracture deformation. At the same time, the AC section is subject to an unevenly distributed load *q*, the intensity of which varies along the AC section depending on its length *X*.

In other words, *q* is a function of *X*. Let us determine the transverse force *Q* and the moment *M* of the soil layer in the AC section.

Transverse force *Q* and bending moment *M* are also functions of *X*.

Considering the transverse force as a sum of elementary forces *q(x)* applied to the layer in sections AB and BC, we find

$$Q(x)=-\int_{x1}^{x2}q(x)dx. \tag{9}$$

Accordingly, *Q(x)* equals the resultant of the distributed load.

In the BC section, the force in the soil layer changes its sign to the opposite. Bending moments in the sections AB and BC are equal in magnitude but oppositely directed. The bending moment can be calculated as

$$M(\alpha)=\pm Rqx, \tag{10}$$

Where *R* is the radius of curvature of the undulating surface, m.

In the section of the convex wave AC, the disruption of the soil layer occurs by tensile and shear deformation due to the alternating loads acting in this zone. In the CF section, the pattern of distribution of the alternating loads is repeated, with the exception that the crushing of the soil layer here occurs by compression deformation.

Along the undulating surface of the TWT, the soil layer under the action of alternating loads is disrupted by tensile and compressive deformations, as well as by bending moment.

Conclusion

Disruption of the soil layer when it is tilled with by existing working tools mainly occurs as a result of shear fracture deformations.

When processing with the proposed toothed working tool due to replicating the complex profile of the working surface of the TWT, there additionally appear compressive, tensile and bending stresses in the soil. The non-uniform deformation field contributes to high quality crushing of the layer during tillage with minimal energy consumption.

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