Determination of the energy intensity of cutting by the working body of the damaged soil layer in the middle of the crater

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Abstract. *The article presents a general view of the working body for cleaning the damaged soil layer inside the crater. In order to select an excavator to which the developed working body is attached, and to determine the requirements for the engine, transmission and fuel consumption, a calculation of the energy intensity of cleaning one cubic meter of contaminated damaged soil layer was carried out.*
KEYWORDS: *AGRICULTURAL SOILS, CRUSH, POLLUTION, WORKING EQUIPMENT, EXCAVATOR BOOM, CUTTING FORCE.*

Introduction

Thousands of hectares of Ukrainian lands were bombed during Russia's full-scale invasion of Ukraine. As a result of rocket and artillery shelling, fields are covered with craters (crashes) from explosions of shells, mines, and rockets. Craters are of various diameters and depths [1]. The depth of craters in the fields ranges from 30 cm (82 mm mortar) to 5 m (cruise missiles), and the soil remaining at the impact site is turbulized, subjected to dynamic compaction, and also contains numerous metal fragments with residues of explosive toxic substances, i.e., the physical properties of soils deteriorate, the grain size changes, compaction, and destructuring occur due to a decrease in the content of agronomically valuable fractions, etc. [2, 3].

To restore the relief, it is necessary to fill in the craters, that is, level the surface. Then, disk cultivation and cultivation can be carried out on this land plot, and if necessary, plowing [4, 5]. If the surface contaminated layer is not cleaned, but the crater is mechanically closed with bulldozers and graders, the restoration of soil fertility will take decades with the need for serious investments in the application of organic fertilizers, ameliorants, phyto-amelioration, etc. [6-8]. Since, in addition to chemical contamination with heavy metals, the fertile soil layer also burns out, dehydration and "sterilization" occur – both pathogenic microorganisms and beneficial biota die [9, 10]. Therefore, the transformation of contaminated land into usable area and the preservation of soil fertility for agricultural purposes is an urgent problem for ensuring food security in Ukraine and the world.

For the technical reclamation of damaged lands as a result of bombing, a method has been proposed that involves first cleaning the craters from damaged and contaminated soil with heavy metals and other hazardous substances. For this purpose, it has been proposed to use a new working body. If a dangerous concentration of heavy metals and other hazardous substances is detected on the surface of the crater, then the removed contaminated soil layer must be disposed of. If the removed layer of the crater surface contains an acceptable concentration of pollutants, then the cleaned layer can be left at the bottom of the crater.

Results and discussion

To remove and clean the damaged surface layer of soil in the crater formed as a result of explosions, it is recommended to use a working body that will allow mechanizing this process. The general view of such a working body is shown in Fig. 1. It consists of a frame in the form of circles, to which channels and angles are welded. The welded structure is reinforced in height with rings made of a metal rod. A bracket for attachment to the excavator boom with the possibility of rotation is welded to the top of the working body.

The working body is fixed on the excavator boom using brackets. Using the hydraulic system, the working body can rotate at an angle and make turns around the axis of the body. Rotating the working body makes it possible to select the angle of inclination of the working body relative to the surface of the crater, the surface layer of which must be cleaned. The edges of the shelves of the channels and angles, which are welded to the working body, will make it possible to remove the top layer of the crater surface and thus free it from damaged molten soil containing heavy metals and other harmful substances. To select an excavator to which the developed working body is attached, and to determine the requirements for the engine, transmission and fuel consumption, a calculation of the energy intensity of cleaning one cubic meter of contaminated damaged soil layer was carried out.

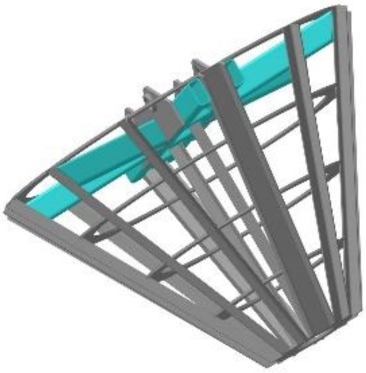

Figure 1. *General view of the working body*

The most significant component of the process of cleaning damaged and contaminated soil by the working body is cutting the soil with shelves of channels and angles, which are welded to the frame circles. The soil model and the scheme of its destruction are adopted with the following assumptions: the soil is considered as a continuous homogeneous isotropic medium, which is characterized by mechanical composition, plasticity, adhesion, internal, external friction and density. The destruction of the contaminated soil layer occurs due to shear and shear deformations after the imbalance of the forces acting on the chip element due to the cutting of the edge of the shelf of the angle or channel. The chip element is considered as a solid body, the resistance to separation of which from the soil medium does not depend on the speed of the working body. Further, as a result of the rotation of the working body, shear deformation of the layer of contaminated damaged soil occurs, which was between the edges of the shelves of the angles and channels. The law of distribution of normal pressure on the shelf surface in the soil shear zone is assumed to be linear along the depth. Destruction during deformation of the soil section by shelves of channels and angles of the working body is carried out with the limitation of the working process by these vertical walls on one side of the shelf. On the other hand, the shelf, when interacting with the soil mass, forms a slot with a one-sided collapse. In this case, the shelf performs blocked asymmetric cutting. The cutting depth *b* will be equal to the length of the shelves of channels and angles of the working body, the cutting length *l* is the length of the channel or angle.

The energy intensity of cleaning one cubic meter of contaminated soil is numerically equal to the shear resistance:

$$E = \frac{1\text{m} \cdot P_{\Sigma V}}{1\text{m} \cdot F} = \frac{P_{\Sigma V}}{l \cdot b}, \left[\frac{kN \cdot \text{m}}{\text{m}^3} \right] \tag{1}$$

where F – the shear area, $F = l \cdot b$; $P_{\Sigma V}$ – the total force that must be applied to the shelves of the working body during their simultaneous interaction, taking into account the speed of movement of the working body during cleaning of the damaged soil layer.

To determine the total force, taking into account the speed of movement of the working body, the formula of V.P. Stanevsky [11] was used:

$$P_{\Sigma V} = m_V \cdot \left[P_\Sigma + \gamma_0 \cdot F \cdot V^{2} \cdot \frac{\sin\delta \sin\theta}{\sin(\delta+\theta)} \right], \quad (2)$$

where m_V – the coefficient of influence of the cutting speed; P_Σ – the total force that must be applied to the shelves of the working body during their simultaneous interaction to clean the damaged soil layer; γ_0 – soil density; V – the speed of movement of the working body during cleaning; δ – cutting angle; θ – the angle between the cleaning trajectory and the prevailing direction of the separated pieces of soil.

The interaction of the shelves of the channels and the angles of the working body when cleaning the damaged soil layer is determined by summing the sum of the values of the cutting forces of one shelf during their simultaneous interaction (Fig. 2). The zones of soil cutting by all shelves of the channels and angles of the working body have the same shape as when cutting by one shelf. We also assume the soil pressure on each shelf to be the same, accordingly the average maximum cleaning force will be equal to the average value.

The total force that must be applied to the shelves of the working body when they interact simultaneously to clean the damaged soil layer:

$$P_\Sigma = n \cdot P, \quad (3)$$

where n – is the number of shelves of the channel or angle that simultaneously interact with the soil; P – is the force that must be applied to one shelf of the channel or angle to clean the damaged soil layer.

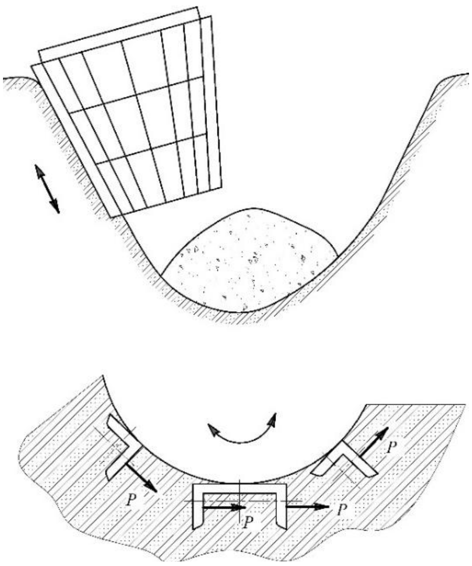

Figure 2. *Diagram of the working body when interacting with damaged soil*

The force that must be applied to one shelf of a channel or angle to clean the damaged soil layer will be equal to:

$$P = P_p + P_z, \quad (4)$$

where P_p – the cutting force of one shelf depends on the following geometric parameters: the width of the cut, the thickness of the cut of the soil layer (cutting depth) and the cutting angle; P_z – the force that arises as a result of the rotation of the working body, i.e., the displacement of the layer of contaminated damaged soil that was between the edges of the shelves of the angles and channels occurs.

Therefore, the force that must be applied to one shelf of a channel or angle to clean the damaged soil layer will be equal according to [12]:

$$P = m_r \cdot b \cdot l \cdot \left(1.78 \cdot \varphi + \frac{2 \cdot m_s}{m_r} \cdot \frac{t}{l} + \frac{2 \cdot m_{sz}}{m_r} \cdot \frac{t}{l} \right), \quad (5)$$

where φ – coefficient, which accounts for the influence of the cutting angle; m_r – generalized index of soil resistance to shear, compression and internal friction when cutting with a sharp knife, N·m^{-2}; m_s, m_{sz} – coefficients characterizing the specific forces for cutting the soil in the lateral expansions of the cut and for overcoming the soil resistance of the cut by the lateral edges of the shelf, N·m^{-2}; t – thickness of the shelf of the channel or angle, m; b – cutting depth, equal to the length of the shelves of the channels and angles of the working body, m; l – cutting length, equal to the length of the channel or angle, m.

Therefore, the total force that must be applied to the shelves of the working body during their simultaneous interaction to clean the damaged soil layer:

$$P_\Sigma = n \cdot m_r \cdot b \cdot l \cdot \left(1.78 \cdot \varphi + \left(\frac{2 \cdot m_s}{m_r} + \frac{2 \cdot m_{sz}}{m_r} \right) \cdot \frac{t}{l} \right), \quad (6)$$

The coefficient of influence of cutting speed is determined by the formula [11]:

$$m_V = 1 + \frac{V}{V_k}, \quad (7)$$

where V_k – critical cutting speed, which is equal to:

$$V_k = \sqrt{\frac{\tau_0}{\gamma_0}} \cdot \frac{\sin(\delta+\theta)}{\cos\delta}, \quad (8)$$

where τ_0 – the maximum allowable stress for a given soil at a velocity close to zero.

In the case when the cutting angle is $\delta = \frac{\pi}{2}$, the critical cutting speed will be equal to $V_k = \infty$, and therefore the cutting speed influence coefficient according to formula (7) $m_V = 1$.

The angle between the clearing trajectory and the prevailing direction of the separated soil pieces is determined by the formula [11]:

$$\theta = \frac{\pi}{4} - \frac{\rho}{2}, \quad (9)$$

where ρ – angle of internal friction of the soil.

Therefore, the total force, taking into account the speed of movement of the working body, is determined by the formula:

$$P_{\Sigma V} = P_\Sigma + \gamma_0 \cdot b \cdot l \cdot V^2 \cdot \frac{\sin\left(\frac{\pi}{4} - \frac{\rho}{2}\right)}{\sin\left(\frac{3\pi}{4} - \frac{\rho}{2}\right)}. \quad (10)$$

As a result of trigonometric transformations and substitution of expression (6) into equation (10), an expression was obtained to determine the total cutting force that must be applied to the shelves of the working body during their simultaneous interaction, taking into account the speed of movement of the working body during cleaning of the damaged soil layer:

$$P_{\Sigma V} = n \cdot m_r \cdot b \cdot l \cdot \left(1.78 \cdot \varphi + \left(\frac{2 \cdot m_s}{m_r} + \frac{2 \cdot m_{sz}}{m_r}\right) \cdot \frac{t}{l}\right) + \\ + \gamma_0 \cdot b \cdot l \cdot V^2 \cdot \tan\frac{\rho}{2} \quad (11)$$

Then the energy intensity of cleaning one cubic meter of contaminated soil is determined by the formula:

$$E = n \cdot m_r \cdot \left(1.78 \cdot \varphi + \left(\frac{2 \cdot m_s}{m_r} + \frac{2 \cdot m_{sz}}{m_r}\right) \cdot \frac{t}{l}\right) + \gamma_0 \cdot V^{2} \cdot \tan\frac{\rho}{2}. \quad (12)$$

Fig. 3 and 4 show graphs of the change in energy intensity of cleaning one cubic meter of contaminated soil from the change in the length of the shelf and the length of the channel and angle in the most energy-intensive version of the working body, i.e. when all its shelves of channels and angles will interact with the damaged soil.

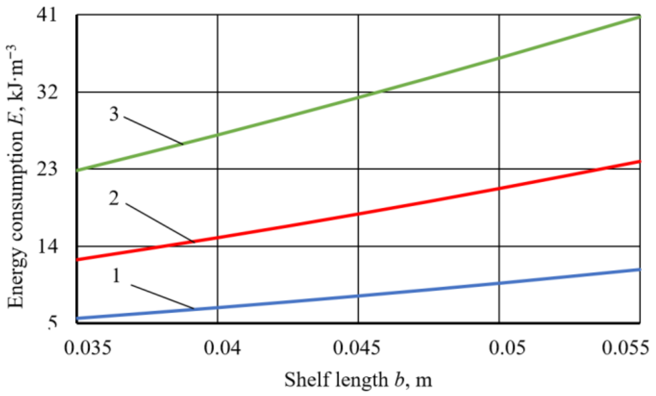

Figure 3. *Graphs of changes in energy intensity E per cubic meter from changes in shelf length b with channel and angle length l = 1 m and velocity V = 0.5 $m \cdot s^{-1}$ for different soil types: 1 – hard sandy loam; 2 – hard loam; 3 – semi-hard clay*

It was found that an increase in the shelf length b within the range of 0.035 m to 0.055 m leads to an increase in the energy intensity E per cubic meter by 47…50%. At the same time, the energy intensity E per cubic meter for the soil type – hard loam increases by 2.1 times, and for semi-hard clay it increases by 3.6…4.1 times compared to hard sandy loam.

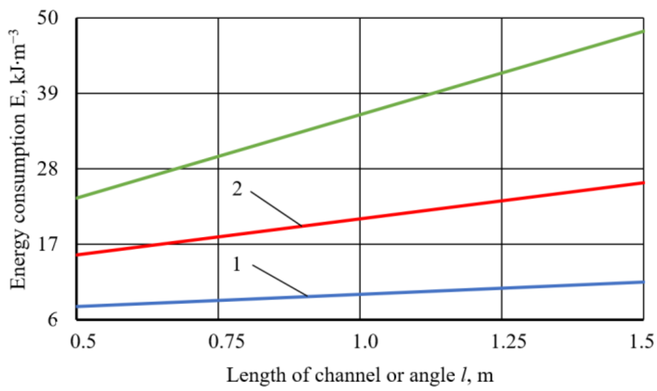

Figure 4. Graphs of changes in energy intensity E per cubic meter from changes in the length of channels and angles l with a shelf length $b = 0.05$ m and a speed $V = 0.5$ $m \cdot s^{-1}$ for different types of soil: 1 – hard sandy loam; 2 – hard loam; 3 – semi-hard clay

Also, increasing the length of channels and angles l within 0.5 m to 1.5 m leads to an increase in the energy intensity E of one cubic meter by 31.3…50.7%. At the same time, the energy intensity E of one cubic meter for the soil type – hard loam increases by 2…2.3 times, and for semi-hard clay it increases by 3…4.2 times compared to hard sandy loam.

Conclusions

The article recommends using a working body that allows for mechanization of this process for removing and cleaning the damaged surface layer of soil inside a crater formed as a result of explosions. A general view of the working body for cleaning the damaged layer of soil inside a crater is presented. In order to select an excavator to which the developed working body is attached, and to determine the requirements for the engine, transmission, and fuel consumption, the energy consumption of cleaning one cubic meter of contaminated damaged soil layer was calculated depending on the length of the shelves of the channels and angles of the working body and the length of the channels and angles themselves.

It is established that an increase in the length of the shelf b within the range from 0.035 m to 0.055 m leads to an increase in the energy intensity E of one cubic meter by 47…50%. At the same time, the energy intensity E of one cubic meter for the soil type – hard loam increases by 2.1 times, and for semi-hard clay increases by 3.6…4.1 times compared to hard sandy loam.

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