INVESTIGATION IN WORKING BODY POWER PARAMETERS AND ENERGY CAPACITY FOR REMOVING DAMAGED SOIL FROM SURFACE OF CRATERS

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Abstract. As a result of the completed research, the impact of the armed aggression and military actions on the soil cover was studied and analyzed, in particular, the damage and destruction of the fertile soil layer due to detonation of various kinds of explosive objects (rockets, aerial bombs, artillery shells, etc.). In consequence of rocket and artillery shelling, the fields are covered with craters from exploding shells, mines, and rockets. The craters are of different diameters and depths. The soil, remaining at the impact site, is turbulent, subject to dynamic compaction, and also contains numerous metal fragments with remnants of explosive toxic substances. To implement technical reclamation of the land, damaged as a result of bombing, a method has been proposed that involves, first, cleaning the craters from the soil damaged and contaminated with heavy metals and other hazardous substances. For this purpose it is proposed to use a new working element that allows for mechanization of this process. The article presents general views of an excavator with an attached working body for removing the damaged soil layer from the (inside) surface of craters. In order to determine rational design parameters of the working body (for removing the damaged soil from the (inside) surface of craters) a study was made of the soil resistance to its cutting into shelves by the channels (channel-shaped cross sections) and angles (angle bars), welded to the circles of the frame (during the process of removing the damaged and contaminated layer of soil from the (inside) surface of the crater). It has been established that increasing the length of shelf *b* within the range from 0.035 to 0.055 m leads to an increase in the cutting force *P* by 44...50%. In addition, the cutting force *P* for the soil type – hard loam increases by 2.1…2.3 times, and for semi-hard clay it increases by 3.6…4.2 times, compared to hard sandy loam. Also, increasing length *l* of channels and angles within the range from 0.5 m to 1.5 m leads to an increase in the cutting force *P* by 32...51%. There is also determined the energy consumption for removing one cubic metre of contaminated soil. It has been established that an increase in length *b* of the shelf within the range from 0.035 to 0.055 m leads to an increase in energy capacity *E* by 47…50%. In addition, the energy intensity *E* for cleaning one cubic metre of the contaminated soil 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. Also, increasing length *l* of channels and angles within the range from 0.5 m to 1.5 m leads to an increase in the energy capacity *E* by 31.3…50.7%. At the same time, the energy intensity *E* of cleaning one cubic metre of the contaminated soil for the soil types – hard loam increases by 2.0…2.3 times, and for semi-hard clay it increases by 3.0…4.2 times, compared to hard sandy loam.

Keywords: agricultural soils, crater, contamination, working body (tool, element), boom of the excavator, cutting force.

Introduction

Thousands of hectares of the Ukrainian land have been bombed during Russia's full-scale invasion of Ukraine. Military actions lead not only to mechanical and physical deterioration of the soil but also to its chemical pollution [1].

Deformation of the soil cover due to the formation of craters from bombing or demining of territories, movement of military equipment, movement of troops, construction of protective structures, and bombing sites lead to disruption of the soil structure. The consequence of this impact is compaction, swamping, and contamination of the territory with the products of military activities [2-4]. The main mechanical impact upon the soil is compaction due to its damage by the humus layer, which has direct negative consequences, such as disruption of the soil water balance and the development of the wind and water erosion. A physical impact involves a change in the physical parameters of the soil as a result of the use of weapons and military equipment, that is, vibration, radioactive and thermal effects. A chemical impact changes the natural physical and chemical parameters of the soil cover, primarily pH, the cation exchange and the humus content. The concentration of toxic chemicals also increases [5; 6].

A combination of various influencing factors leads to the emergence of a cumulative negative effect. The consequences are the loss of the buffering capacity of soils for restoration, the loss of humus and a decrease in their natural fertility [7]. Therefore, the transformation of the contaminated lands into usable areas and the preservation of the fertility of the agricultural soils is a pressing issue how to ensure the food security in Ukraine and in the world.

To restore the relief, it is necessary to fill in the craters, that is, to level their surface. Then disking and cultivation may be carried out on this plot of land, and, if necessary, ploughing. If the contaminated surface layer is not cleared away but the crater is mechanically levelled with bulldozers and graders, the restoration of the soil fertility will take decades and will need serious investments into the application of organic fertilizers, ameliorants, phytomelioration, etc.

Therefore, to remove the damaged surface layer of the soil in the crater, formed as a result of an explosion, it is recommended to use a working body that allows for mechanization of this process.

Materials and methods

In order to remove and clean the damaged surface layer of the soil in a crater, formed as a result of an explosion, it is recommended to use a working body that will allow mechanization of this process. This working body is attached to the boom of an excavator with a hydraulic system. Fig. 1 depicts a general view of an excavator with an attached working body for removing the damaged soil layer from the (inside) surface of the crater, and a general view of this working body.

Boom 2 is attached to the platform 1 via an articulated joint. Hydraulic cylinders 3, 4, 5 are attached to the boom 2, which ensure turning of the handle 6, to which the working element 8 in the form of a cut cone is attached via the bracket 7. It is proposed to make this working body active, that is, performing rotational movement with the help of a hydraulic motor, connected to the hydraulic network of the excavator.

The working body (Fig. 1, b) consists of a frame in the form of circles to which channels (channel-shaped cross sections) and the angle bars (angles) are welded. The welded structure is reinforced in height with rings, made of metal rods. A bracket is welded to the top of the working body for its mounting onto the excavator boom, with an ability to turn. The working body is fixed to the excavator boom using brackets. By means of the hydraulic system the working body can turn at a certain angle and make turns around the longitudinal axis of the body. The turning of the working body makes it possible to select the angle of the working body relative to the surface of the crater, the surface layer of which must be cleaned. The ribs of the layers of the channels and angles, which are welded to the working body, make it possible to remove the upper layer of the crater surface and thus free it from the layer of the damaged soil, containing heavy metals and other harmful substances. The ribs of the channel and the angle, which are welded to the working body, make it possible to remove the top layer of the crater surface and thus free it from the damaged layer of the molten soil, containing heavy metals and other harmful substances.

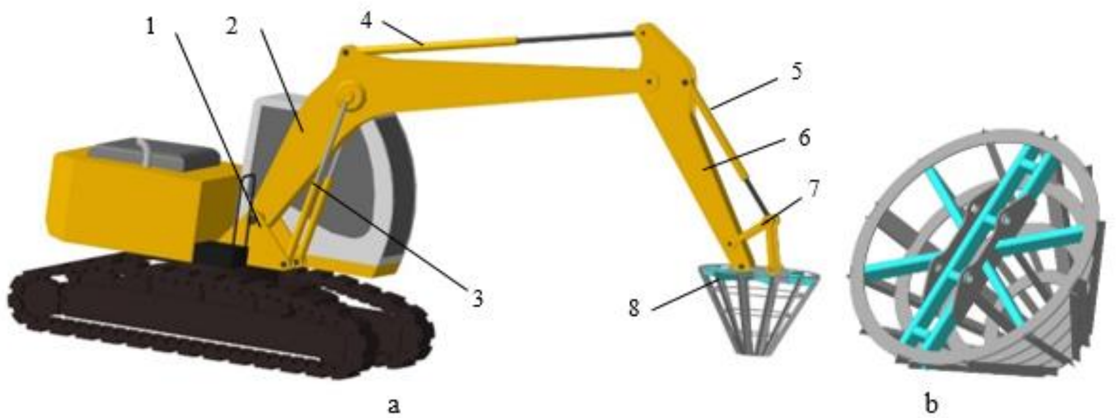

Fig. 1. **General view of an excavator with an attached working body for removing the damaged soil from the inside layer of the craters (a), and a general view of this working body (b):** 1 – platform; 2 – boom; 3, 4, 5 – hydraulic cylinders; 6 – handle; 7 – bracket; 8 – working body

In order to determine rational design parameters of the working body for removing the damaged layer of soil from (the surface of) the craters, research was conducted on the resistance of the soil to its cutting into shelves by the channels and the angles, welded to the circles of the frame during the process of removing the damaged and contaminated soil layer from the surface of the crater.

The most significant component of the process of cleaning the damaged and contaminated soil by means of the working body is cutting the soil into shelves by the channels and angles, welded to the frame circles. The separation of shavings from the mass of soil takes place in layers under conditions of blocked asymmetric cutting of the soil. 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 layer of soil occurs as a result of shear deformations after the balance of the forces, acting onto the shavings element, is disturbed due to the deformations of cutting of the edge of the shelf of the angle (the square) or channel into the soil. In addition, the shavings element is considered as a solid body that resists separation from the soil environment, independent of the speed of the working body. Further, as a result of turning of the working body, there occurs shear deformation of the layer of the contaminated damaged soil, which is located between the edges of the shelves of the angles and channels. The law of distribution of normal pressure along the surface of the shelf in the landslide zone along the depth is adopted as linear.

Destruction during deformation of the soil, cut into shelves of channels and angles of the working body takes place with limitation of the working process along the vertical walls on one side of the shelf. On the other side of the shelf, when interacting with the mass of soil, a one-way camber slot (gap) is formed. In this case, the shelf performs a blocked asymmetrical cut. The cutting depth b will be equal to the length of the shelves of the channel or square of the working body, the cutting length l will be equal to the length of the channel or the square bar l.

To determine the cutting force that must be applied to the working body to remove the damaged soil layer, one shelf of a channel or an angle is considered, the calculation scheme for which is shown in Fig. 2.

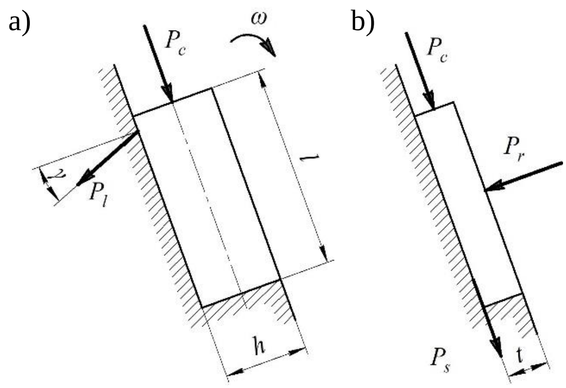

Fig. 2. **Calculation scheme for determination of the cutting force on one shelf of a channel or an angle of the working body:** a – front view; b – side view

The cutting force of the shelf depends on the following geometric parameters: the width of the cut, the thickness of the soil layer cut (the cutting depth) and the cutting angle [8].

The interaction of the shelf with the soil is of spatial nature. In order to determine the influence of spatial interaction, all the forces of the blocked cutting are decomposed into three components: forces P_r to overcome the resistance of the soil in front of the front edge of the shelf, proportional to the area of the cut in front of the frontal edge and dependent on the cutting angle and the strength of the soil; forces P_l to overcome the resistance of the soil during destruction in the lateral extensions, proportional to their cross-sectional areas, which depend on the strength of the soil and do not depend on the cutting angle and the width of the cut; forces P_s to overcome the resistance of the cut by the lateral working shelves at the bottom of the cut, proportional to the thickness of the cut, depending on the strength of the soil and independent of the cutting angle and the width of the cut.

The total cutting force of a shelf of the channels or the angles is equal to [8]:

$$P_c = P_r + P_l + P_s \,. \tag{1}$$

As a result of turning of the working body, there is also a shear deformation of the layer of the contaminated damaged soil which is located between the edges of the shelves of the angle bars and channels. When this layer is displaced, a force of the soil resistance P_{sh}. will arise.

Consequently, the force that must be applied to one shelf of a channel or an angle to remove the damaged layer of the soil will be equal to:

$$P = P_c + P_{sh} = \varphi \cdot m \cdot b \cdot l + 2 \cdot m_l \cdot b \cdot t + 2 \cdot m_s \cdot b \cdot t + 0.78 \cdot \varphi \cdot m \cdot b \cdot l \,, \tag{2}$$

or:

$$P = m \cdot b \cdot l \cdot \left(1.78 \cdot \varphi + \frac{2 \cdot m_l}{m} \cdot \frac{t}{l} + \frac{2 \cdot m_s}{m} \cdot \frac{t}{l}\right), \tag{3}$$

where φ – coefficient, taking into account the impact of the cutting angle;
m – generalized indicator of the soil resistance to shear, compression and internal friction during destruction when cutting with a sharp knife, $N \cdot m^{-2}$;
m_l, m_s – coefficients that characterize the specific forces for soil destruction in lateral expansions and for overcoming the soil shear resistance by lateral working shelves, $N \cdot m^{-2}$;
t – thickness of a shelf of a channel or an angle, m;
b – cutting depth, equal to the length of the shelves of channels and angles of the working body, m;
l – length of the cut, equal to the length of the channel or angle, m.

The interaction of the shelves from channels and angles of the working body during cleaning of the damaged soil layer is determined by summing the values of the cutting forces of one shelf during their simultaneous interaction (Fig. 3). The zones of soil destruction by all the shelves of channels and angles of the working body have the same shape as in the case of destruction by one shelf. It is also assumed that the soil pressure onto each shelf is the same, and, therefore, the average maximum cleaning force will be equal to the average value.

Then the total force that must be applied to the shelves of the working body during their simultaneous interaction in order to clear away the damaged soil layer will be equal to:

$$P_\Sigma = n \cdot m \cdot b \cdot l \cdot \left(1.78 \cdot \varphi + \left(\frac{2 \cdot m_l}{m} + \frac{2 \cdot m_s}{m}\right) \cdot \frac{t}{l}\right), \tag{4}$$

where n – number of shelves of the channel or the angles that simultaneously interact with the soil.

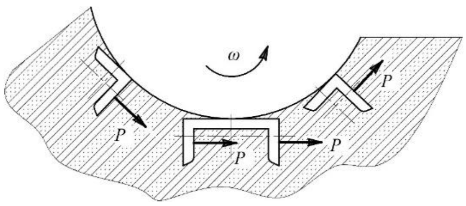

Fig. 3. **Scheme of the working body when interacting with the damaged soil**

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

$$E = \frac{1\text{m} \cdot P_{\Sigma V}}{1\text{m} \cdot F_{sh}} = \frac{P_{\Sigma V}}{l \cdot b} \tag{5}$$

where F_{sh} – cutting area, $F_{sh} = l \cdot b$;
$P_{\Sigma V}$ – 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 when clearing the layer of the damaged soil.

As a result of substitutions and transformations, an expression was obtained for determination of 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 when clearing the layer of the damaged soil:

$$P_{\Sigma V} = n \cdot m \cdot b \cdot l \cdot \left(1.78 \cdot \varphi + \left(\frac{2 \cdot m_l}{m} + \frac{2 \cdot m_s}{m}\right) \cdot \frac{t}{l}\right) + \gamma_0 \cdot b \cdot l \cdot V^2 \cdot \tan\frac{\rho}{2} \tag{6}$$

where γ_0 – soil density;
V – speed of movement of the working body during cleaning;
ρ – the angle of internal friction of the soil.

The energy consumption for cleaning one cubic metre of the contaminated soil is determined by the formula:

$$E = n \cdot m \cdot \left(1.78 \cdot \varphi + \left(\frac{2 \cdot m_l}{m} + \frac{2 \cdot m_s}{m}\right) \cdot \frac{t}{l}\right) + \gamma_0 \cdot V^{2.} \cdot \tan\frac{\rho}{2} \cdot \tag{7}$$

Therefore, using equations (3) and (7) it is possible to determine the cutting force that must be applied to one shelf of the channel and the angle to remove the layer of the damaged soil, and the energy consumption for this purpose.

Results and discussion

Based on the calculation program, created on PC, data were obtained that made it possible to construct graphical dependencies of the energy indicators, depending on the design parameters of the developed working element. Figs. 4 and 5 show graphs of the dependence of the cutting force P which must be applied to one shelf of the channel and angle to remove the damaged layer of the soil, on the length of the shelf b and the length of the channel l and the angle.

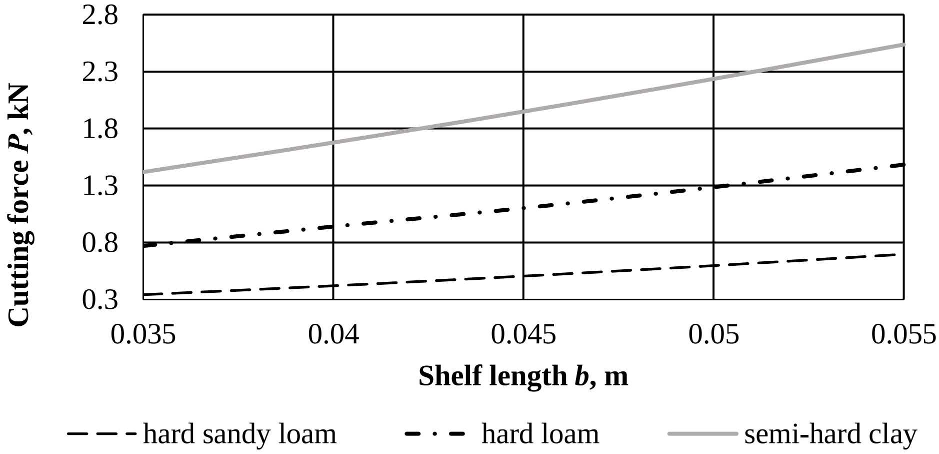

Fig. 4. **Dependence of the cutting force *P* upon the length of the shelf b at the length of channels and angle bars *l* = 1 m for various types of soil**

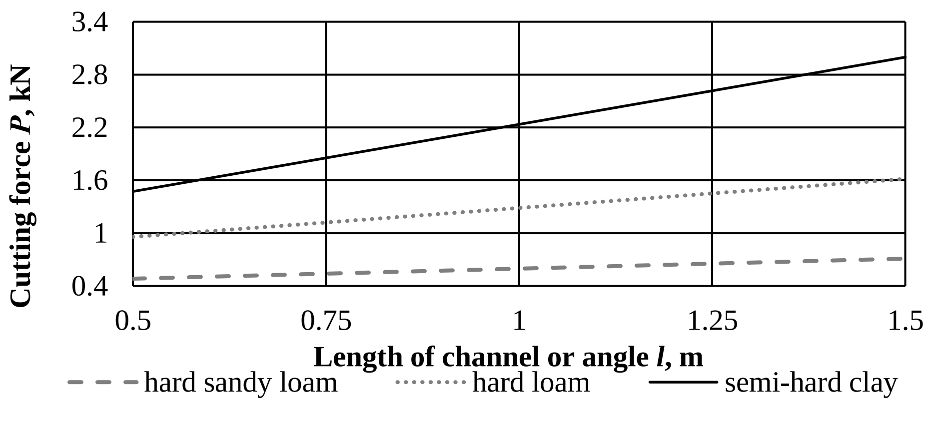

Fig. 5. **Dependence of the cutting force *P* on the length l of the channel sand angle bars at the length *b* = 0.05 m of the shelf (layer, row) for various types of soil**

It has been established that increasing the length b the shelf within the range from 0.035 to 0.055 m leads to an increase in the cutting force *P* by 44...50%. Besides, the cutting force *P* for the soil type – hard loam increases by 2.1…2.3 times, and for semi-hard clay it increases by 3.6…4.2 times, compared to hard sandy loam. Also, increasing the length *l* of channels and angles within the range from 0.5 m to 1.5 m leads to an increase in the cutting force *P* by 32...51%. In this case the cutting force *P* for the soil type – hard loam increases by 2...2.3 times, and for semi-hard clay it increases by 3...4.3 times, compared to hard sandy loam.

Fig. 6 and 7 depict the graphs of dependence of the energy intensity for cleaning one cubic metre of contaminated soil upon the length of the shelf and the length of the channel and the angle in the most energy-intensive version of the working body, i.e. when all shelves of the channels and angles interact with the damaged soil.

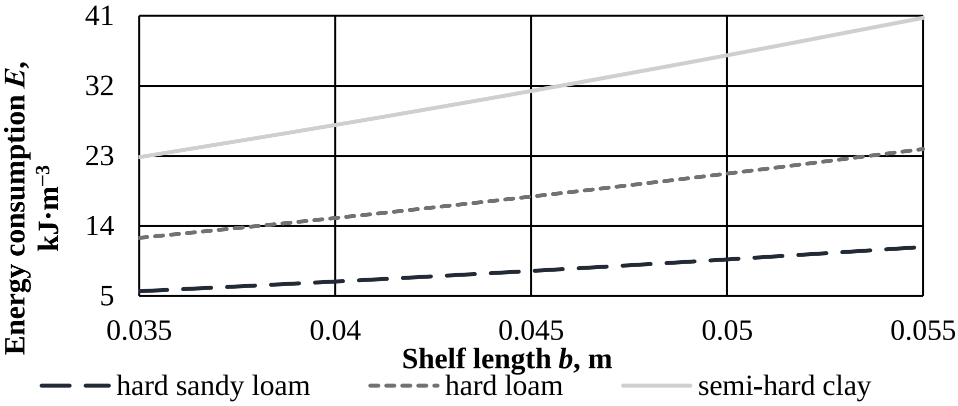

Fig. 6. **Dependence of the energy intensity E for cleaning one cubic metre of contaminated soil on the shelf length b with the channel and angle length *l* = 1 m and the speed:** $V = 0.5$ m·s^{-1} for various types of soil: 1 – hard sandy loam; 2 – hard loam; 3 – semi-hard clay

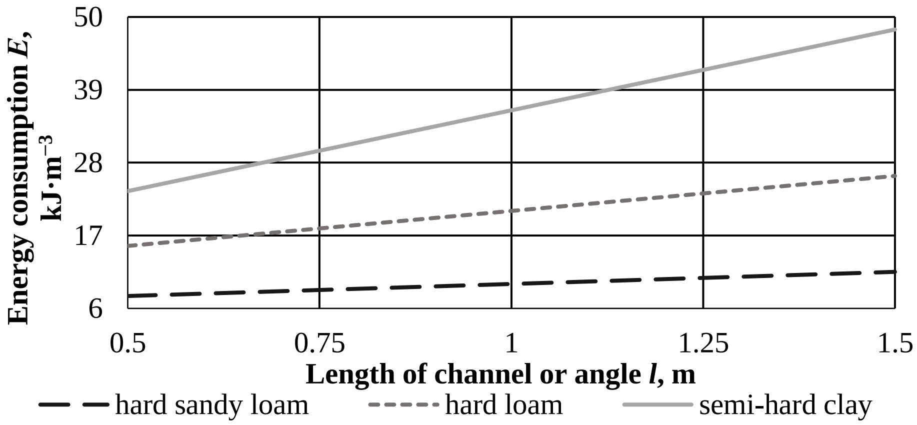

Fig. 7. **Dependence of the energy intensity *E* of cleaning of one cubic metre of contaminated soil on the length *l* of channels and angle bars at the shelf length *b* = 0.05 m and velocity *V* = 0.5 m·s^{-1} for different types of soil**

It has been established that an increase in the shelf length *b* within the range from 0.035 to 0.055 m leads to an increase in the energy intensity *E* of cleaning one cubic metre of the soil, contaminated to 47...50%. Besides, the energy intensity *E* for cleaning one cubic metre of contaminated soil 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.

Also, increasing the length of channels and angles within the range from 0.5 m to 1.5 m leads to an increase in the energy intensity *E* for cleaning one cubic meter of contaminated soil by 31.3…50.7%. In addition, the energy intensity *E* for cleaning one cubic metre of contaminated soil 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.

The literary data suggest that the tactical and non-tactical military operations affect nature. An armed conflict has multiple effects on the natural resources from the global to a regional scale [9]. Russia's invasion of Ukraine has resulted in unprecedented impacts on the soil, water, air quality, flora and fauna. Studies of the war-affected soils consist mainly of publications on soil contamination as a result of military actions in Ukraine [1, 10-14]. The ongoing war in Ukraine has already resulted in a wide range of soil disturbances unparalleled in Europe since World War II [9]. Since Ukraine makes a significant contribution to the global food market, the war has upset the balance of global food security [15]. In addition, the soil disturbances in Ukraine are accompanied by intensive anti-mine actions, which has led to a decrease in the soil fertility [1] and a reduction in the share of agricultural territories [16], which contributes to the problem of global food security [17].

Therefore, the transformation of contaminated lands into usable areas and the preservation of the fertility of agricultural soils is a pressing issue for ensuring food security in Ukraine.

A method is proposed in this article that involves, first, cleaning the craters of damaged and contaminated soil with heavy metals and other hazardous substances. For this purpose it is put forward to use a new working element that allows the process to be mechanized. If a dangerous concentration of heavy metals and other hazardous substances is detected on the surface of the crater, 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 removed layer can be left at the bottom of the crater. Next, to restore the relief, it is necessary to fill in the craters, that is, to level the surface. Then, on this plot of land we can make disking and cultivation, and, if necessary, ploughing.

Conclusions

1. The article presents general views of the developed working body and an excavator with an attached working element for scraping off the damaged soil layer from the surface of craters in an agricultural field that were formed as a result of explosions.
2. In order to determine rational design parameters of the working body for cleaning the damaged soil inside the craters, a research was conducted on the effect of the soil cutting force of the shelves of the channels and angles, welded to the circles of the frame. It has been established that increasing the length of the shelf b within the range from 0.035 to 0.055 m leads to an increase in the cutting force P by 44...50%. In addition, the cutting force P for the soil type – hard loam increases by 2.1…2.3 times, and for semi-hard clay it increases by 3.6…4.2 times, compared to hard sandy loam. Also, increasing the length l of channels and angles within the range from 0.5 m to 1.5 m leads to an increase in the cutting force P by 32...51%.
3. There was determined the energy consumption for cleaning one cubic metre of contaminated soil. It has been established that an increase in the length b of the shelf within the range from 0.035 to 0.055 m leads to an increase in the energy capacity E by 47…50%. In addition, the energy intensity E for cleaning one cubic metre of the contaminated soil 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. Also, increasing the length l of channels and angles within the range from 0.5 m to 1.5 m leads to an increase in the energy capacity E by 31.3…50.7%. At the same time, the energy intensity E of cleaning one cubic metre of the contaminated soil for the soil types – hard loam increases by 2.0…2.3 times, and for semi-hard clay it increases by 3.0…4.2 times, compared to hard sandy loam.

Author contributions

Conceptualization, V.B.; methodology, A.R. and O.G.; software, G.P.; validation, A.A.,A.R. and V.B; formal analysis, V.B and I.H..; investigation, V.B., Z.R., G.P. and I.B.; data curation, A.A.,A.R., V.B. an V.V.; writing – original draft preparation, V.B.; writing – review and editing, A.A., A.R. and I.B.; visualization, O.T., A.R.; project administration, V.B.; funding acquisition, V.V. All authors have read and agreed to the published version of the manuscript.

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