INVESTIGATION IN ENERGY PARAMETERS OF PROCESS OF COMPACTED SOIL TRANSPORTATION BY FLEXIBLE SECTIONAL SCREW CONVEYOR

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Abstract. The article presents a design scheme of an experimental setup, which is a machine-tractor aggregate with a mounted system and a flexible screw conveyor, that will allow disposal of the removed contaminated soil layer and its loading into the truck body. In order to improve the functional and operational performance of the process of recycling the removed contaminated soil layer, an analytical dependence has been derived for the determination of the capacity of transportation of the removed damaged soil layer by a flexible sectional screw conveyor with a variable main line. From the analysis of the graphical dependencies, it was established that, with an increase in the angle of inclination of the material transportation trajectory, the values of the energy-power parameters of the conveyor increase, but an increase in the pitch of the screw turns in the direction of movement of the material leads to a decrease in the energy-power parameters of transportation.

Keywords: damaged contaminated layer of soil, flexible screw conveyor, transportation.

Introduction

The state of the soil resources in many countries of the world is currently characterized by a rapid decline in their fertility, caused by a sharp decrease in the amount of humus, as well as the impact of various negative impacts, associated with increased erosion processes, including salinization, alkalization, etc. All this causes significant damage to agricultural production. However, in the countries where military conflicts are taking place, in particular the war currently being waged in Ukraine, in addition to this, significant physical processes of destruction of the upper fertile soil layer are taking place. As a result of high-power explosions, not only deep (sometimes up to 8-10 m) and large-area craters are formed in agricultural fields but also deep soil rocks are ejected to the surface and scattered over the adjacent territory; and the internal surfaces of craters from explosions are contaminated with various chemical elements (sometimes phosphorus, heavy and radioactive metals), which contribute to deep penetration into the surface layer due to high explosive temperatures. As a result, in most cases, the internal surfaces of the explosion craters form a solid sintered surface of sufficient thickness (in the form of a crust), contaminated with dangerous chemical elements. In addition, the wheeled and tracked systems of the heavy military equipment intensively destroy the structure of the upper fertile soil layer, forming quite deep ruts. In many cases, because of military necessity, trenches, deep dugouts, and shelter elements were built in the thickness of the earth's surface on most fertile areas of agricultural fields.

Thus, as a result of numerous rocket and artillery attacks, agricultural fields are covered with craters from exploding shells, mines and rockets, which have different sizes and often shapes. It should be noted that the size and shape of the explosion craters change over time, both under the impact of natural factors and as a result of continued military action. However, our research has shown that the chemical composition of the damaged soil changes very slowly over time. So, it was established that in the composition of the soil, damaged as a result of the explosions, toxic chemical elements remain in almost the same quantities. In these layers of the damaged soil there remain for a long time traces of radioactive elements, fragments of various sizes, metal shavings, sintered from high temperatures and significantly compacted soil aggregates that are difficult to dissolve in water [1-3].

All this indicates that the natural deactivation of chemically hazardous compounds within the contaminated soil layer, as well as the natural restoration of the fertility of such soil, are very unlikely. Special purposive agrochemical and agroengineering measures are needed to restore the soil fertility, damaged by military action.

In addition, the restoration of the surface relief of agricultural fields, i.e. the levelling of fields, which have changed as a result of numerous explosions and the movement of significant volumes of it in various directions, remains an urgent problem.

These actions should be aimed at the reclamation of the damaged soil and can be carried out, using such a technology. In the case when it is established through chemical analysis that the contamination of the soil inside the craters because of explosions remains within acceptable limits, then it is necessary to use mechanization to ensure the "return" of the deep soil masses to the depth from which it was raised to the surface as a result of the explosion. Next, the crater should completely be filled, trying to place the fertile parts of the soil on top. And finally, to ensure complete levelling of the relief.

In case a chemical analysis of the soil inside the crater, especially on its lateral surface, shows contamination that exceeds the established standards, then it is necessary to first collect all contaminated soil from the crater and take it to special places where it will be decontaminated or disposed of [4]. The contaminated soil, which may be located outside the blast crater itself (sometimes scattered over significant distances) must also be collected and removed for disposal. After that, according to the above scheme, it is necessary to first collect the deep layers of soil and transport it to the bottom of the craters, and then to fill them with a fertile layer of soil, and finally level the outer surface.

The main question remains how to collect the contaminated soil layer from the lateral surface inside the crater and load it into vehicles to be removed for disposal. Our research has shown that it is most rational, first, to remove the inner surface and the baked layer of the contaminated soil from the lateral surface of the crater, using a simple mechanical method, then the removed layers will fall down under their own weight and fill its bottom. Next it is necessary to capture this mass of contaminated soil and lift it up to the level of the vehicle body, which will then take it to the disposal or decontamination site. If the issue of cleaning the caked contaminated soil layer at the bottom of the explosion crater is not a complicated technical task, then its collection and transportation can be completed in several ways. The most suitable for this purpose is the use of screw conveyors, in particular, the flexible screw conveyor that we have developed, in which the screw winding is formed by separate elements – the screw curvilinear sections, which are connected by means of articulated joints, which ensure its flexibility [5].

However, the existing flexible screw conveyors cannot fully meet the operational requirements for such types of conveyors. The use of shaftless flexible auger spirals leads to their rapid destruction when the conveyors operate on curved routes due to the arising alternating cyclic loads. It has been established by our experimental investigations that the transportation capacity of a flexible screw conveyor for bulk materials, including fine soil, is sufficiently high. However, there is a complication in the design of such flexible screw conveyor, which, in turn, causes an increase in its metal consumption, causing an increase in the energy costs for transportation of soil [6-8].

So one of the most pressing tasks to restore the fertility of agricultural soils, damaged as a result of military actions, i.e. collecting of the contaminated soil and transporting it to the decontamination or disposal sites, is the development of such mechanization tools that would not only efficienly perform this technological process, but would also be with as low energy intensity as possible. This concerns, first of all, the search for opportunities to reduce the energy consumption for the collection and transportation of the crushed contaminated soil in the body of the vehicle, using a specially designed screw conveyor.

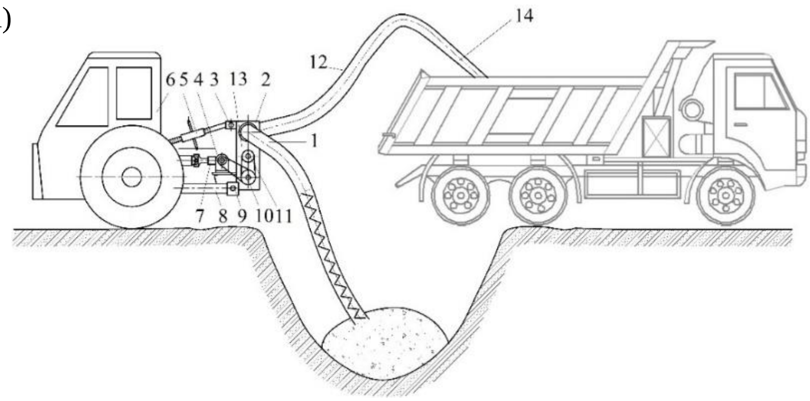
Materials and methods

A flexible screw conveyor with a sectional working screw element can be used for the disposal of the contaminated soil layer, removed and dumped to the bottom of the crater. This will provide a possibility to transfer the contaminated soil, scraped off the bottom of the crater, into the body of the vehicle. Fig. 1 shows the design diagram of the device that we have developed in the form of an experimental setup, which, using the rear hitch of a wheeled tractor and a power take-off shaft, connected to the rear shaft, sets flexible screw conveyors into rotational movement. By means of this experimental setup, it is possible to conduct in real field conditions investigaions of the process of capturing the soil from below and transporting it into the body of a vehicle at a pre-set height.

This conveyor consists of flexible casings 1 and 12, through which loading and unloading are carried out, respectively. Coaxially with the flexible casings from the opposite side of the transfer pipe

2 on the drive shafts are located sprockets 10, 13, which are kinematically connected to the intermediate shaft 11 by means of chain drives.

a)



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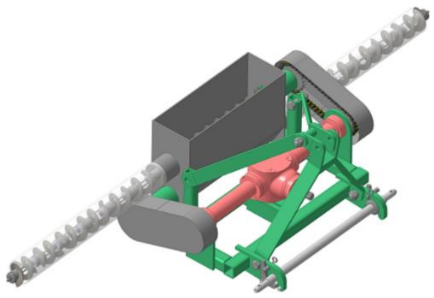

Fig. 1. **Structural diagram of the experimental setup with a mounted system of a machine-tractor aggregate (a) and a general view of the experimental setup of a flexible screw conveyor (b):** 1 – flexible casing for loading; 2 – reloading pipe; 3 – upper bracket; 4 – gearbox shaft; 5 – central rod; 6 – machine-tractor aggregate; 7 – cardan transmission; 8 – lower bracket; 9 – output shaft; 10 – sprocket; 11 – intermediate shaft; 12 – unloading flexible casing; 13 – sprocket; 14 – longitudinal rod

The lower 8 and the upper 3 brackets are installed on the body of the transfer pipe. Through brackets 3 and 8, the conveyor is connected to the central 5 and longitudinal 14 suspended rods of the machine-tractor unit system 6. The gearbox 4 is connected via a chain transmission to the output shaft 9 of the unloading line, while gearbox 4 is driven into rotational motion by means of cardan transmission 7 from the power take-off shaft of the tractor. The intermediate shaft 11 also can be as the output shaft of gearbox 4, the axis of which is located in a plane, equidistant from the drive shafts of the main lines, which in turn will lead to simplification of the drive design (Fig. 1, a).

During their operation the rotation of the flexible screw sectional articulated working parts of the conveyor is achieved by using kinematically connected drive shafts, an intermediate shaft and a power take-off shaft of the machine-tractor aggregate.

The disposal of the removed contaminated soil layer is made in the following sequence. First, the loading casing, together with the flexible screw sectional hinged working element is installed in the middle of the crater. In addition, the conveyor screw captures the cleared soil, by means of a self-loading opening. Then, due to the rotation of the working element, the cleared soil is transported in the casing towards the transfer pipe of the experimental setup and, with the help of the unloading casing with a flexible screw sectional working element, to the unloading zone in the body of the vehicle.

In Fig. 2 there is shown the design diagram of a flexible screw sectional working body for transporting damaged soil. This working body consists of separate sections of identical diameters and lengths which are made in the form of welded structures, containing rods 1, to which a cylindrical sleeve 2 is rigidly fixed at one end, made with a system of axial parallel grooves, which are placed evenly around the circle and interact with balls 3. From the other side balls 3 interact with the spherical holes of body 4, which enables axial and angular turning of the spherical pin 5.

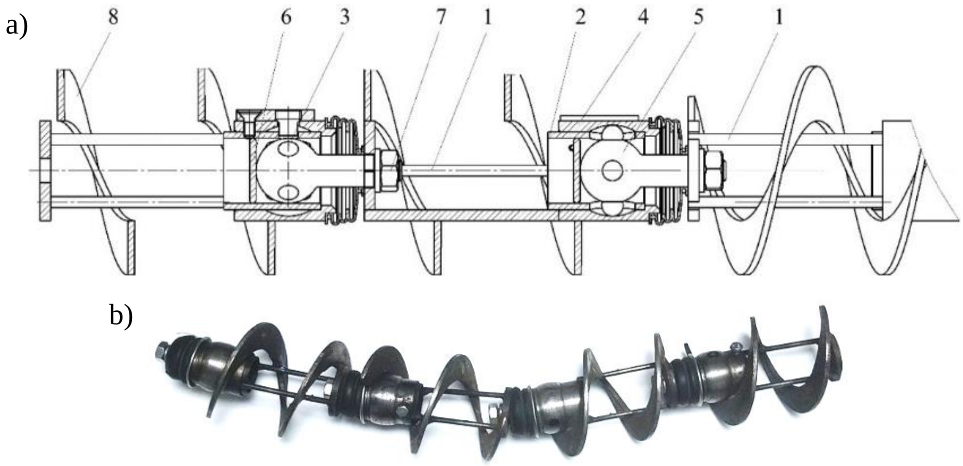

Fig. 2. **Structural diagram (a) and general view (b) of a flexible screw sectional working body:** 1 – rod; 2 – cylindrical sleeve; 3 – balls; 4 – body; 5 – spherical pin; 6 – connecting sleeve; 7 – bolt connection; 8 – screw section

In addition, from above the cylindrical sleeve 2 is in rigid interaction with the spherical body 4, the inner surface of which interacts with the outer surfaces of balls 3. From the second end of the welded cylindrical section, a connecting sleeve 6 is rigidly installed into the internal opening, perpendicular to the axis, interacting with the corresponding end of the spherical pin 5 of the adjacent section, with its rigid fixation using a bolted connection 7.

To the outer diameter of the cylindrical section there is rigidly welded a screw section 8.

The principle of operation of the screw working element is as follows: the rotational movement from rotation of the spiral section 8 is transmitted through balls 3 to the spherical pin 5 and adjacent sections of the screw working element, as a result of which the rotation of the next section of the screw auger occurs.

Determination of energy-power parameters will improve the performance of the flexible screw sectional working bodies and ensure a reduction in energy costs for the process of transportation the cleared damaged soil layer in the crater.

To move the soil along the casing of the flexible screw conveyor, it is necessary to perform work A_1 and A_2 to overcome the forces of its friction against the surface of the screw spiral and the casing, respectively, and work A_3 of the movement process for the disposal of the removed contaminated soil layer. Also during transportation, the material is mixed; besides, work A_4 is performed.

The total work of transportation is determined by the formula:

$$A = A_1 + A_2 + A_3 + A_4 \,. \tag{1}$$

Components A_1 and A_2 of the total work are small, compared to others, and in practical calculations can be estimated by the corresponding coefficients.

According to the experimental data [9], as a first approximation:

$$A_4 = A_h \cdot e^{-\vartheta(\rho_h - \rho)} \,, \tag{2}$$

where A_h – work of movement;
ρ – speed coefficient of the movement;
$\rho = \omega^2 \cdot R_c \cdot g^{-1}$; ω – angular velocity of the cleared damaged soil;
R_c – external radius of the screw spiral;
g – acceleration of gravity, g = 9.81 m·s^{-2};
ρ_h – coefficient of speed at maximum soil movement;
ϑ – coefficient of speed influence.

In order to study the process of movement for disposal of the contaminated soil layer (work A_3), removed by the flexible screw conveyor with a sectional working element, it is necessary to determine the axial velocity of the soil in a horizontal high-speed screw conveyor, the axial velocity in the case of transporting the cleaned soil at angle α to the horizon, and the speed of axial transportation of the material by a vertical section of the flexible screw conveyor.

For this purpose we used the dependencies which we obtained earlier, presented in article [10]:

– the axial velocity of soil in a horizontal high-speed screw conveyor:

$$V_{ax} = \frac{T_s \omega}{2\pi} \cdot \frac{k_s}{\tan\theta \cdot \tan(\theta + \varphi) + 1}, \tag{3}$$

where T_s – pitch of the helical spiral;
φ – angle of friction of the material along the surface of the helical spiral;
φ = arctan μ_1 ; μ_1 – coefficient of the soil friction along the surface of the helical spiral;
θ – inclination angle of a section of the helical spiral;
k_s – coefficient that takes into account the influence of the design of the sectional screw conveyor.

The axial velocity in case of transportation of the cleared soil at angle α to the horizon:

$$V_{ax\alpha} = V_{ax} \cdot \left(1 - \sqrt{\frac{\tan(\theta + \varphi)}{\mu_2 \cdot \rho}}\right), \tag{4}$$

where μ_2 – coefficient of the soil friction along the surface of the conveyor casing.

The velocity of axial transportation of the material by the vertical section of the flexible screw conveyor is:

$$V_{axB} = \frac{T_s \omega}{2\pi} \cdot \frac{k_s \cdot \left[1 - \sqrt{\frac{g \cdot \tan(\theta + \varphi)}{\omega^2 \cdot \mu_2 \cdot R_c}}\right]}{\tan\theta \cdot \tan(\theta + \varphi) + 1}. \tag{5}$$

To utilize the removed contaminated soil layer, using a flexible screw conveyor with a sectional working element, the main line must change in space, and loading must occur horizontally (Fig. 3). Therefore, the significance of the change in speed V_α along the transportation route is extremely important.

In the case of a freely suspended screw conveyor, the axis of the flexible screw has the form of a catenary line, which changes according to the law [10]:

$$y = a \cdot \left(\mathrm{ch}\frac{x}{a} - 1\right), \tag{6}$$

where a is a parameter that depends on the height of the discharge opening and is determined from the following relationship:

$$\frac{h}{a} + 1 = \mathrm{ch}\left(\frac{l_x}{a}\right), \tag{7}$$

where h – height of the material elevation;
l_x – horizontal projection of the conveyor casing length.

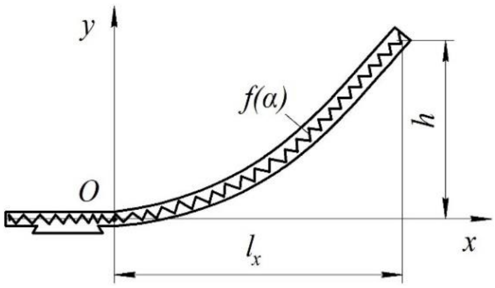

Fig. 3. **Scheme of the loading casing of a flexible screw conveyor**

Therefore, according to [10], for a freely suspended flexible sectional screw conveyor, the axial velocity of the soil movement will be equal to:

$$V_{ax\alpha} = V_h \cdot \left[1 - \frac{1}{\omega} \cdot \sqrt{\frac{g \cdot \tan(\theta + \varphi)}{\mu_2 \cdot R_c}} \cdot \left(\frac{2 \arctan\left(\mathrm{sh} \frac{x}{a} \right)}{\pi} \right)^{\lambda} \right], \tag{8}$$

where λ – parameter that depends on the rheological properties of the cleared damaged soil, and at first approximation it can be taken as $\lambda = 2$.

Therefore, the curve that describes the position of the flexible screw can be considered a parabola, and the dependence of speed V_α upon the angle can be considered parabolic.

The performance of the flexible screw conveyor for moving the removed contaminated soil layer during the disposal was determined according to the following relationship:

$$Q = \pi \cdot \psi_o \cdot V_{ax\alpha} \cdot \left(R_c^2 - r_c^2 \right), \tag{9}$$

where r_c – inner radius of the screw spiral;
R_k – radius of curvature of the transportation line.

The capacity of the screw conveyor with a variable conveying line is determined from the following relationship:

$$N = Q \cdot L \cdot w, \tag{10}$$

where L is the length of transportation; w is the specific energy intensity of transportation [10; 11]:

$$w = \frac{\mu_2 \cdot \gamma \cdot R_k \cdot R_c^2 \cdot \omega_f^2 \cdot \omega \cdot \cos\beta}{V_f}, \tag{11}$$

where γ – specific density of soil;
ω_f – angular velocities of adjacent sections;
V_f – axial speed of soil transportation by the flexible sectional working element of screw conveyor along curved route;
β – angle of inclination of soil transportation trajectory.

From the performed calculations it was established that the angular velocities of adjacent sections are practically the same [7].

The elementary capacity for transportation of the cleared soil for a flexible sectional screw conveyor with a variable route on site dl is determined by the formula:

$$dN = Q \cdot w(l) \cdot dl, \tag{12}$$

where

$$w(l) = \frac{\mu_2 \cdot \gamma \cdot R_k \cdot R_c^2 \cdot \omega \cdot \left(\omega - \frac{2 \cdot \pi \cdot V_{ax\alpha}}{T_s} \right)^2 \cdot \cos\left[\beta(l) \right]}{V_f(l)}.$$

Angle of inclination β of the trajectory of transportation of the contaminated soil is determined from dependence [10]:

$$\tan\beta = \frac{V_{ax\alpha}}{\omega_{f\alpha} \cdot R_c} = \frac{V_{ax\alpha}}{\left[\omega - \frac{2 \cdot \pi \cdot V_{ax\alpha}}{T_s} \right] \cdot R_c}. \tag{13}$$

Consequently, the transportation capacity of the cleared layer of the damaged soil by a flexible sectional screw conveyor with a variable route is determined according to the following relationship:

$$N_s = Q\int_0^L w(l)\cdot dl = Q\cdot \mu_2 \cdot \gamma \cdot R_k \cdot R_c^2 \cdot \omega \cdot \int_0^L \frac{\left(\omega - \frac{2\cdot\pi\cdot V_{ax\alpha}}{T_s}\right)^2 \cdot \cos\beta}{V_h^2} dl \,. \tag{14}$$

The calculated power, used by one flexible casing of a screw conveyor, taking into account A_4, equations (18) and (24) and other energy costs, is determined by the following relationship:

$$N = k_m \cdot k_0 \cdot \pi \cdot \psi_o \cdot R_k \cdot R_c^2 \cdot \left(R_c^2 - r_c^2\right)\cdot \mu_2 \cdot \gamma \cdot \omega \cdot \int_0^L \frac{\left(\omega - \frac{2\cdot\pi\cdot V_{ax\alpha}}{T_s}\right)^2 \cdot \cos\beta}{V_h} \cdot dl \,, \tag{15}$$

where k_m – coefficient that takes into account the costs of mixing, crushing, and grinding the soil;
k_0 – coefficient of power consumption in bearing assemblies and chain transmission.

The total power, used by the flexible screw conveyor, is determined by the following expression:

$$N_f = N_1 + N_2 \,, \tag{16}$$

where N_1 – power, used by the loading casing of the flexible screw conveyor;
N_2 – power used by the unloading (discharge) casing.

Consequently, by means of equation (16) it is possible to determine the required power of the flexible screw conveyor, which must be used from the machine-tractor aggregate.

Results and discussion

Based on the calculation program, compiled on PC, numerical calculations were performed, which made it possible to construct graphical dependencies of the change in power for the drive of one flexible screw, depending on the design and operational parameters.

In Fig. 4 there are shown graphs of the change in power for the design of one flexible screw conveyor casing from the change in the angle of inclination of the soil transportation trajectory and the pitch of the screw threads *T*.

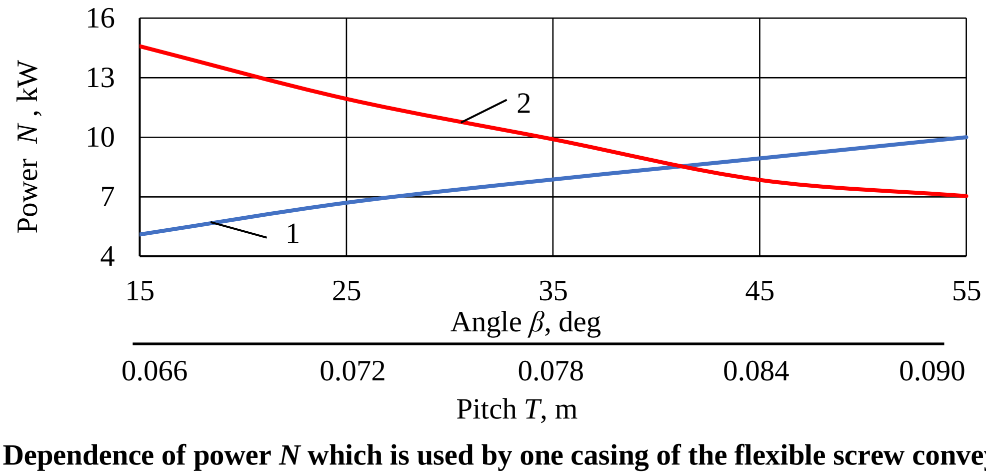

Fig. 4. **Dependence of power *N* which is used by one casing of the flexible screw conveyor upon the change of:** 1 – angle of inclination of the soil transportation trajectory; 2 – pitch *T* of the screw threads

From the graphs, presented in Fig. 4, it is evident that the nature of the change in curve 1 is close to linear, which indicates that with an increase in the angle of inclination of the trajectory of transportation of the cleared damaged soil, the power, used by one casing of the flexible screw conveyor, increases proportionally. It is also evident that with an increase in the angle of inclination of the material transportation trajectory within the range from 15° to 55°, the power used by one flexible screw conveyor casing increases by 1.96 times.

Further, also from the graphs, presented in Fig. 4, it is evident that curve 2 has a form, close to the exponential nature of the change, and a more intensive decrease in the power *N* occurs at the pitch *T* of the screw windings up to 0.085 m; with further increase in the pitch size T the consumed power decreases insignificantly. With an increase in the pitch T of the screw turns within the range from 0.066 m to 0.09 m, it decreases by 2.07 times. On the whole, to decrease the power, consumed by one casing of the flexible screw spiral, the step value T should be selected within the range of 0.085… 0.09 m.

From the analysis of the theoretical research of the working bodies of flexible screw conveyors [12-14], it can be concluded that the overwhelming majority of authors derived analytical dependencies in order to establish the functional, operational and design parameters of the flexible screw working bodies. In addition, there have not been resolved the issues of substantiating the parameters of the screws that ensure their high functional and operational parameters with the minimum permissible mass (weight) of the working element. This will essentially reduce the energy costs for the movement process and the degree of damage of the bulk and lump agricultural material.

The experimental results presented in this paper relate to the spirals of the screw without using a flexible shaft. However, as the experimental investigations and tests have shown, when transporting the material along a curved route (especially at small radii of curvature), as a result of the occurrence of cyclic alternating deformations, the screw spirals are destroyed quite quickly, which sharply limits the use of such working bodies due to the failure to meet, first of all, the operational requirements. In order to increase the reliability of the technological process during the development and research of the working elements, the following should be used: a sectional method for manufacturing working elements (to eliminate significant cyclic loads); an increase in the contact area between the torque transmission units, which will reduce internal stresses and forces in the friction pairs by increasing the torque transmission arm.

Conclusions

1. With an increase in the angle of inclination of the material transportation trajectory within the range from 15° to 55°, the power used by one flexible screw conveyor casing increases by 1.96 times, and with an increase in the pitch T of the screw turns within the range from 0.066 m to 0.09 m, it decreases by 2.07 times. The article shows the design scheme of an experimental setup with a mounted system of a machine-tractor aggregate and a general view of a flexible screw conveyor, which can be used for the disposal of a layer of the removed contaminated soil.
2. In order to improve the functional and operational performance of the process of recycling the layer of the removed contaminated soil layer, an analytical dependence has been derived for the determination of the transporting capacity of the cleaned damaged soil for a flexible sectional screw conveyor with a replaceable main line.
3. Based on the conducted research, it was established that with an increase in the angle of inclination β of the material transportation trajectory, an increase in the energy-power parameters of the conveyor is observed, and an increase in the pitch T of the screw windings in the transportation direction helps reduce these indicators.

Author contributions

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

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