STUDY OF DEVICE WITH FLEXIBLE SCREW CONVEYOR FOR REMOVING DAMAGED SOIL CLEARED FROM CRATER

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Abstract. To study the process of disposing contaminated soil scraped from the inside of a crater, this article utilizes a newly developed design of a device with a sectional flexible screw conveyor, which allows transporting loose contaminated soil scraped from the side surface of the crater's interior and accumulated at its bottom. The aim of this study is to determine the productivity of this process, specifically the productivity of the aforementioned device. Based on the results of the developed program and methodology, as well as the experimental studies conducted with this device, indicators characterizing the collection and transport of disturbed soil were obtained and processed using statistical methods. Based on this, corresponding regression equations, response surfaces, and their two-dimensional cross-sections were constructed to determine the influence of controlled factors on the performance of the flexible screw conveyor during soil transport. The research results obtained make it possible to select the optimal technological and kinematic parameters of the developed device based on a flexible sectional screw working body, which allows effective collection and transport of excavated contaminated soil from the interior of the pit and its loading into the body of a transport vehicle for removal and disposal.

Keywords: loose contaminated soil, pit, unloading device, screw conveyor, auger, transportation, productivity.

Introduction

In modern agricultural conditions, it has become possible for fertile lands to be significantly damaged as a result of military operations, particularly due to powerful explosions of shells and mines, which leave deep craters on their surfaces. Even taking into account the fact that, during explosions, layers of infertile soil are brought to the surface from a certain depth and scattered over a large area around the craters, the interior of the craters themselves contains heavily contaminated, hardened soil that must be collected and removed for disposal or decontamination. As a result of explosions caused by modern weaponry, the inner surface of the craters contains highly dangerous substances, such as phosphorus, heavy metals, and even radioactive components.

Thus, in this case, there is not only mechanical damage of fertile soil, which subsequently requires painstaking and labor-intensive efforts to restore the surface relief, but also dangerous chemical and even radioactive contamination of the soil cover.

The release of heavy metals into the natural environment during ground combat operations and bombings is caused by weapon residues containing Pb, Cu, Cd, Sb, Cr, Ni, and Zn, which subsequently migrate into water sources, thereby increasing the risk of human exposure. Biomonitoring studies have shown the accumulation of heavy metals in plants, invertebrates, and vertebrates [1].

To restore areas damaged by explosions, it is necessary to mechanically remove or scrape off the topsoil and transport it away for decontamination.

Therefore, transforming contaminated lands into usable areas and preserving the fertility of agricultural soils is a pressing scientific and technical challenge.

Several studies and published scientific works have already been dedicated to addressing this problem. It has been established that, to restore the fertility of affected soils and put them back into use, it is insufficient to merely clear mines and subsequently backfill all existing craters [2-4]. It is also recommended that the topsoil be removed or cleared for this purpose, since, in addition to chemical contamination with heavy metals, the fertile soil layer is also significantly depleted [5]. It has been established that if the contaminated surface layer is not removed, but the crater is mechanically backfilled using bulldozers and graders, the restoration of soil fertility will take decades. This will necessitate significant investments in the application of organic fertilizers, soil conditioners, phytoremediation, and other measures [6-8].

In addition, a method has been proposed for the technical reclamation of land damaged by bombing, which involves clearing the craters of damaged soil contaminated with heavy metals and other hazardous substances [9].

It has been demonstrated that a device consisting of a flexible screw conveyor with sectional working elements can be used to dispose of the removed contaminated soil layer; this device makes it possible to scoop the contaminated soil from inside the pits and transfer it into the body of a transport vehicle [10].

Transporting the excavated soil using flexible screw working elements enclosed in elastic casings ensures high productivity and mobility during the technological process, thereby expanding their technological capabilities and reducing energy consumption [11-13]. In [14], a methodology is proposed for determining the technological parameters that ensure reduction in energy consumption during the movement of bulk materials.

Based on the results of a literature review and the studies conducted in [15, 16], the structural, kinematic, and technological parameters of the working elements of a flexible screw conveyor were substantiated from the perspective of their functional purpose. At the same time, a number of issues related to the operational characteristics and service life indicators of these working bodies remain insufficiently studied. This indicates that improving the operational efficiency of flexible screw conveyors is an important and pressing task in agricultural production.

The aim of this study is to determine the performance of a device with a flexible screw conveyor for unloading damaged soil removed from the interior of a pit.

Materials and methods

To transport loose damaged soil scraped from the inside of a pit, a new device was developed that utilizes a flexible screw conveyor, enabling the soil to be transferred into a truck bed. Fig. 1 shows a schematic diagram of this device. The device consists of a frame 1, to which loading 2 and unloading 3 flexible conveyors are attached, consisting of fixed casings and flexible sectional screw conveyors.

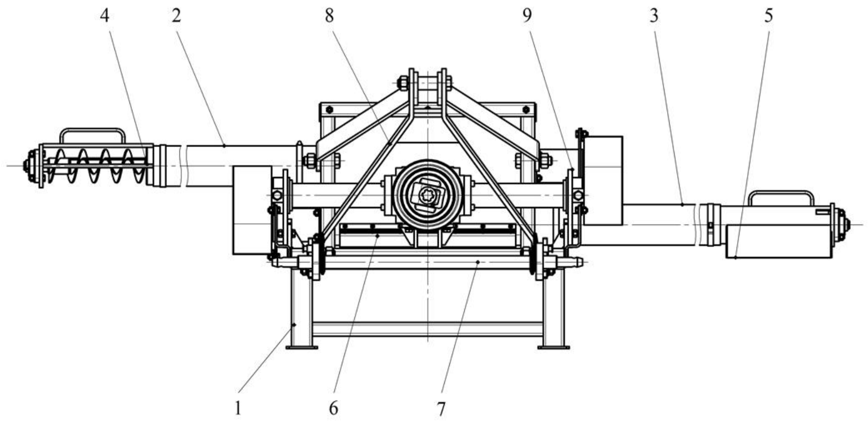

Fig. 1. **Schematic diagram of a device with a flexible screw conveyor:** 1 – frame; 2 – loading line; 3 – unloading line; 4 – self-loading opening; 5 – unloading opening; 6 – transfer pipe; 7 – intermediate shaft; 8 – lower bracket; 9 – upper bracket

The inlet duct housing 2 is equipped with a self-loading opening 4 at one end, while the outlet duct housing 3 has an opening 5 for discharging material. At the other ends, both casings are connected to the drive shafts of the transfer pipe 6. Coaxial with the flexible line casings, on the other side of pipe 6, the shafts of the screw-type sectional augers are kinematically connected to the intermediate shaft 7 via chain drives. The lower 8 and upper 9 brackets are mounted on the body of the transfer pipe 6, by means of which the conveyor is attached to the power take-off shaft of the mounted system of a Class 1.4 machine-tractor unit. During operation, the kinematically linked drive shafts of the flexible screw sectioned augers, the intermediate shaft, and the power take-off shaft of the machine-tractor unit ensure rotation of these conveyor working elements. It has been established that this power is sufficient to ensure the rotation of both the loading and unloading sections of the device.

To transport loose, cleared, damaged soil, the loading line with a flexible screw sectional auger was installed in the center of the pit. The conveyor's working element picks up the soil through the self-loading opening and, as it rotates, transports it inside a stationary flexible casing toward the conveyor's transfer pipe, after which, through the discharge chute with a flexible sectional screw conveyor, it feeds the material into the unloading zone – into the body of the transport vehicle.

Fig. 2 shows the general design of a flexible screw conveyor for transporting excavated damaged soil.

Experimental studies were conducted to determine the productivity of the device with a flexible screw conveyor for unloading damaged soil scraped from the interior of the pit. A program and methodology were developed for these studies, and a model of a multifactorial experiment was constructed based on the measurement results.

Thus, to determine the influence of independent factors on the transport capacity of the flexible screw conveyor under study, a comparative multifactorial experiment of the PFE-3^3 type was conducted.

To this end, experimental studies were conducted with the following variable parameters: screw rotation speed, n, rpm; lifting height of the loose soil, h, m; and the soil filling coefficient of the conveyor line, ψ, i.e., $Q = f(n, h, \psi)$. The experimental studies were conducted with a loose soil conveyor length of 4 m. The conveyor motor was started and its rotational speed was controlled using an Altivar 71 frequency converter; the results of the studies, obtained using PowerSuite v.2.5.0 software, were displayed on a computer screen, which allowed for a smooth start and control of the rotational speed of the screw conveyor's electric motor shaft.

a) b)

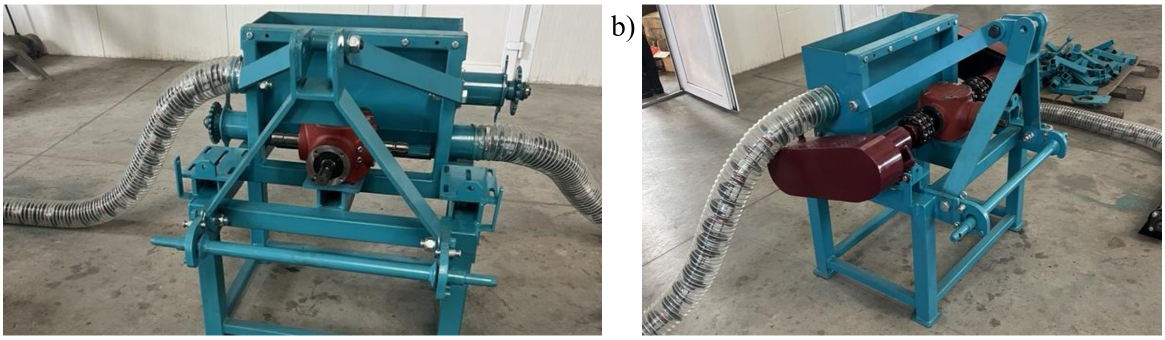

Fig. 2. **General view of the device with a flexible screw conveyor for transporting cleared damaged soil:** a – front view; b – side view

The experiments were conducted under a stable conveying process, i.e. when the material filled the entire length of the transfer pipe and the main lines. The material was collected into a measuring container, and the time required to fill the container was recorded. The material was then weighed on an electronic scale and its volume measured using a measuring container.

Separate experimental studies were conducted to determine the filling coefficient ψ. To this end, the volume occupied by the transported material and the amount of this material that ended up in the measuring container were assessed over a specific period of time as it passed through the transport line. The measurement error was 1 g for the electronic scales and 0.1 s for the stopwatch. In the experiments, loamy soil with a moisture content of 10-20% was used, with soil particle cohesion in the range of 0.04-0.06 MPa, the bulk density was 1300-1600 kg·m^{-3}, the angle of natural repose was 30-40°, and the soil particle size distribution consisted of the following components: sand 50%, silt 35%, and clay 15%.

In conducting the experiments, the selected controlled factors are heterogeneous; they have different units of measurement, and the numbers expressing the values of these factors have different orders of magnitude. Therefore, they must be converted to a unified calculation system by converting from actual values to coded values.

The results of coding the variable factors and their levels of variation are presented in Table 1. After coding the factors, a design matrix was created for the corresponding 3^3 factorial experiment for a total of $N = 3^3$ trials.

When implementing the compiled plan matrices, to eliminate the influence of uncontrolled and unregulated factors on the transport capacity of the studied device with a flexible screw conveyor, we randomized the plan matrix using the random balance method, which was implemented by drawing experiment numbers from a box.

The function of the optimization parameter, transport capacity $Q = f(n, h, \psi)$, is presented in the form of a mathematical model of a full quadratic polynomial [14].

Table 1

Results of factor coding and levels of variation in the study of transport productivity

Factors	Designation		Interval Variation	Levels of variation, natural/coded		
	Code	Natural				
Screw rotation frequency, *n*, rpm	X_1	x_1	200	300/–1	500/0	700/ + 1
Lifting height of bulk material *h*, m	X_2	x_2	1.0	1/–1	2/0	3/ + 1
Filling coefficient, ψ	X_3	x_3	0.2	0.3/–1	0.5/0	0.7/ + 1

After performing calculations and statistical analysis of the research results, a regression equation for productivity during transport by a flexible screw conveyor was obtained. It takes the form:

$$Q = 5.4804 + 0.7548 \cdot x_1 - 0.4348 \cdot x_2 + 1.16 \cdot x_3 - 0.0952 \cdot x_1 \cdot x_3 - 0.144 \cdot x_1^2 - 0.098 \cdot x_3^2 . \quad (1)$$

As can be seen, the expression given in (1) contains the constant term $b_0 = 5.4804$ and coefficients reflecting the influence of each factor x_i on the productivity value, which are equal to $b_1 = 0.7548$, $b_2 = -0.4348$, and $b_3 = 1.16$, respectively. It has also been established that productivity is influenced by the combined effect of two factors with a coefficient $b_{13} = 0.0952$ and their quadratic effects $b_{11} = -0.144$ and $b_{33} = -0.098$.

The adequacy of the selected mathematical model was verified against experimental data – that is, the correspondence of the mathematical model to the real process – using the Fisher criterion (F). In this case, the obtained value (F_p) was compared with the tabulated value (F_T).

The calculated value of the Fisher criterion is $F_p = 1.2359$, and the corresponding tabulated value is $F_T = 1.965$ at a 5% significance level. Thus, the condition of adequacy of the selected mathematical model is satisfied, i.e. the PFE regression equation is consistent with the experimental data.

The multiple correlation coefficient was also determined, which was equal to $R = 0.928$. Accordingly, the regression equation for productivity in natural coordinates during transportation using a flexible screw conveyor, after transformation and simplification of the expressions, will take the form:

$$Q = -0.9793 + 0{,}0086 \cdot n - 0.4348 \cdot h + 9.44 \cdot \psi - 0.000036 \cdot n^2 - 0.0024 \cdot n \cdot \psi - 2.45 \cdot \psi^2 . \quad (2)$$

The resulting regression equation (3) can be used to study the influence of the main technological and kinematic parameters of a flexible screw conveyor on its transport capacity, i.e. to determine how transport capacity depends on the following factors: screw rotation speed n (rpm), lifting height of bulk material h (m), and the filling coefficient of the conveyor with soil, ψ, within the following ranges: $300 \le n \le 700$ (rpm); $1 \le h \le 3$ (m); $0.3 \le \psi \le 0.7$.

Results and discussion

Based on the results of calculations performed using the “Statistica 13.0” software package for processing and analyzing experimental research data, we constructed three-dimensional spatial dependencies of the performance response surfaces for transportation by a device with a flexible screw conveyor and their two-dimensional cross-sections to visually represent the results of the experimental studies, and determine the effects of the factors and their interaction on the optimization parameter, i.e. $Q = f(n, h, \psi)$.

We performed computer calculations, which enabled us to obtain three-dimensional graphs and their two-dimensional cross-sections, as shown in Fig. 3-5. The figures show the performance response surfaces and their two-dimensional cross-sections as a function of two variable factors $x_{i\,(1,2)}$ at a constant level of the corresponding third factor $x_{i\,(3)}$ = const. To examine the value of the third factor, a value equal to the factor’s value at the zero level was selected.

Analysis of the given regression equation shows that the dominant factor influencing the throughput when transporting with a flexible screw conveyor is the soil filling coefficient of the conveyor, ψ. The material lift height h and the working body rotation speed n also significantly affect the change in productivity.

When the pipeline soil filling coefficient ψ varies between 0.3 and 0.7, the productivity increases by 33%; when the material lift height h increases between 1 and 3 m, the productivity decreases by 17%; and when the rotational speed of the working body n varies from 300 rpm to 700 rpm, the productivity increases by 16%.

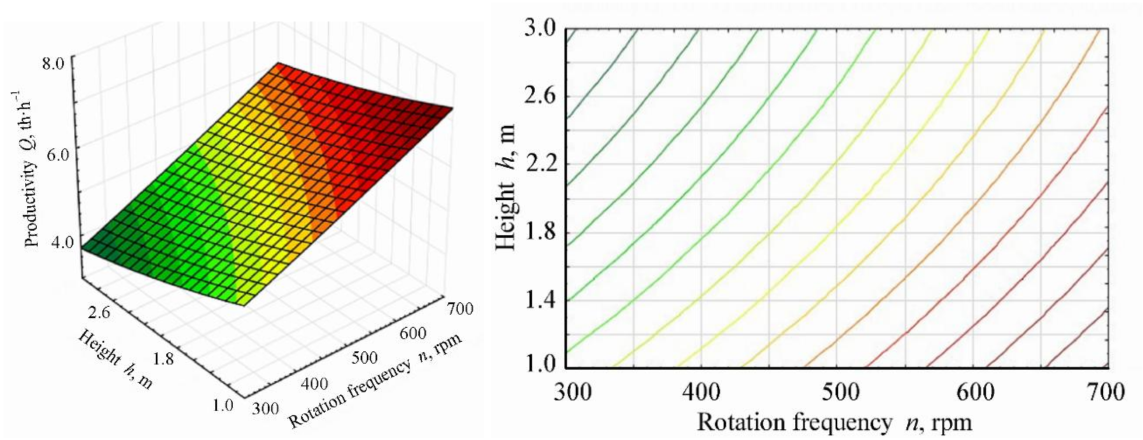

Fig. 3. **Response surface (left) and its two-dimensional cross-section (right) for transportation by a device with a flexible screw conveyor: $Q = f(n; h)$**

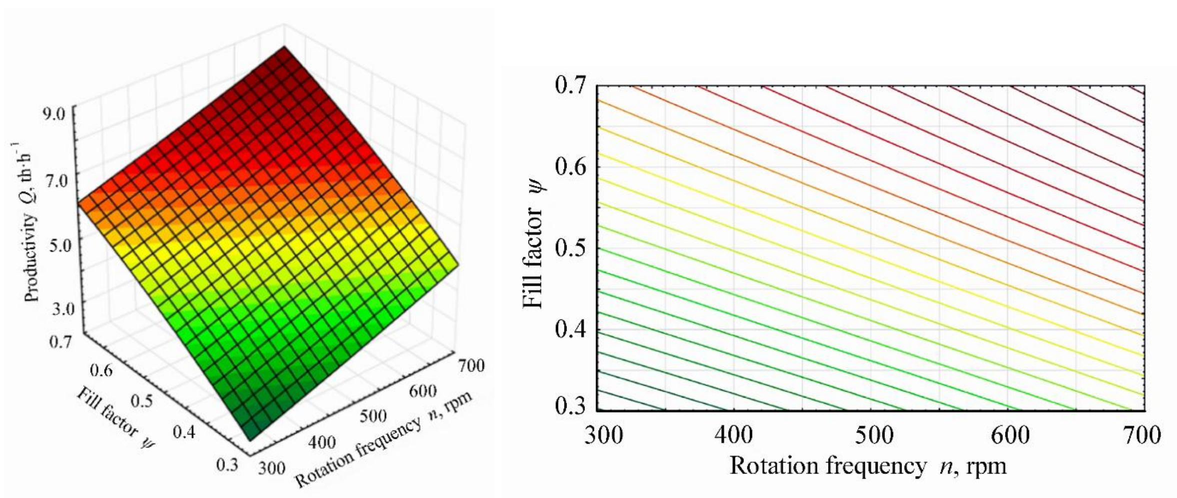

Fig. 4. **Response surface (left) and its two-dimensional cross-section (right) for transportation by a device with a flexible screw conveyor: $Q = f(n; \psi)$**

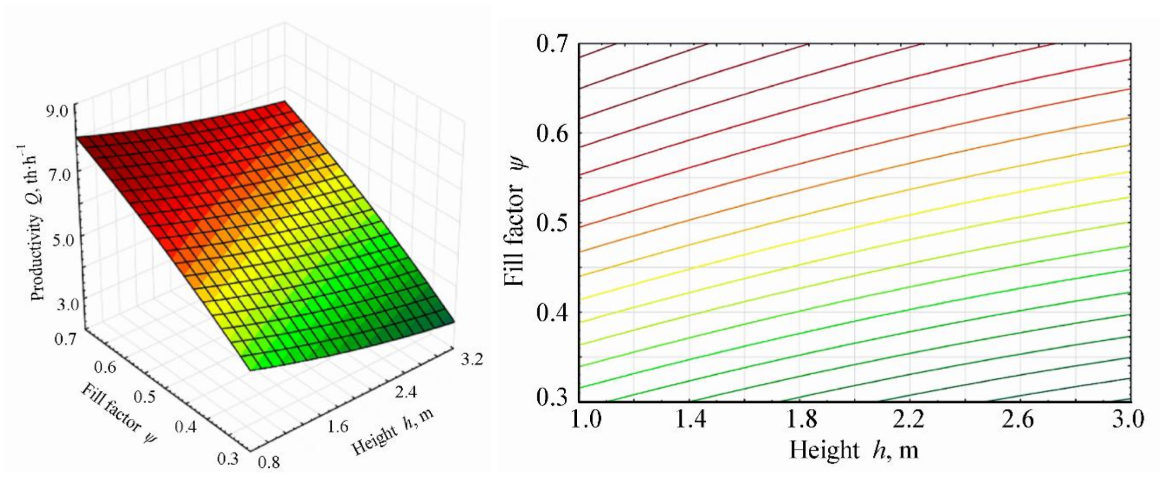

Fig. 5. **Response surface (left) and its two-dimensional cross-section (right) for transportation by a device with a flexible screw conveyor: $Q = f(h; \psi)$**

The results of the conducted research justify the selection of optimal design, kinematic, and technological parameters for the developed sectional screw working body during the transportation of excavated contaminated soil from the center of the pit.

Conclusions

1. The article presents the design diagram and general view of a device with a flexible screw conveyor, which allows transportation of bulk material along curved paths for removal of bulk material scraped from the side surface of the pit and accumulated at its bottom.
2. A methodology for conducting experimental studies of the device with a flexible screw conveyor has been developed.
3. A multifactorial experiment was conducted to study the influence of the screw rotation speed, the lifting height of the scraped soil, the soil filling coefficient of the main line on the productivity of the device with a flexible screw conveyor.
4. Analysis of the given regression equation shows that the dominant factor influencing the productivity of a flexible screw conveyor system is the soil filling coefficient, ψ. The material lift height h and the rotational speed of the working body n also significantly affect changes in productivity. When the soil filling coefficient ψ varies within the range of 0.3-0.7, the productivity increases by 33%; when the material lift height h increases within the range of 1-3 m, the productivity decreases by 17%; and when the rotational speed of the working body n varies from 300 rpm to 700 rpm, the productivity value increases by 16%.

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