UDC 504.062:608.2
DOI: 10.15587/1729-4061.2022.263513

IMPROVEMENT OF QUARRY AND SLAGHEAP RECLAMATION TECHNOLOGY

Yaroslav Baikalov
Corresponding author
Postgraduate Student
Department of Environmental Protection
Donetsk National Technical University
Shybankova sq., 2, Pokrovsk, Ukraine, 85300
E-mail: yaroslavbaikalov@gmail.com
Iryna Dzhygyrey
PhD, Associate Professor
Institute of Applied Systems Analysis***
Vladyslav Bendiuh
PhD, Associate Professor
Department of Mathematical Methods of System Analysis ***
Oleg Proskurnin
Doctor of Technical Sciences, Senior Researcher, Leading Researcher
Laboratory of Problems of Formation and Regulation of Water Quality
Research Institution "Ukrainian Research Institute of Environmental Problems"
Bakulina str., 6, Kharkiv, Ukraine, 61166
Kateryna Berezenko
Senior Lecturer
Department of Horticulture and Ecology
Luhansk Taras Shevchenko National University
Kovalya str., 3, Poltava, Ukraine, 36014
Public Organization "Balanced Development – East"
Rapniy lane, 2, Sloviansk, Ukraine, 84110
Sergii Boichenko
Doctor of Technical Sciences, Professor
Department of Ecology
Educational and Research Institute of Energy Saving and Energy Management
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy str., 37, Kyiv, Ukraine, 03056
Anatoliy Kryuchkov
PhD, Associate Professor*
Mykola Serhiienko
Lecturer*
Oleksandr Danilin
PhD, Associate Professor
Department of Automation of Electrical and Mechatronic Complexes**
Oleksii Kutniashenko
PhD, Associate Professor
Department of Environmental Protection
Donetsk National Technical University
Shybankova sq., 2, Pokrovsk, Ukraine, 85300
*Department of Geoengineering**
Educational and Research Institute of Energy Saving and Energy Management*
***National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy str., 37, Kyiv, Ukraine, 03056

This paper considers and analyzes a relevant issue of treatment of disturbed soils. The equipment to carry out various processes of mining reclamation of waste heaps and quarries with a significant reduction in the level of environmental risks through the operation of an energy-saving small-sized apparatus has been designed. The use of the developed soil reclamator is also adequate for pre-sowing and other types of agrotechnical tillage, plant care in agricultural fields, as well as in areas with a heterogeneous landscape. The functionality of the unit is able to provide energy autonomy and automation of the technological process. The low weight of the device makes it possible to reduce the pressure on the soil, which minimizes the environmentally hazardous formation of dust during the treatment of waste heaps, the destruction of its structure, the machine degradation of the fertile layer during the processing of all types of territories. The device also reduces the risk of fertile soils slipping from the slopes of mine dumps due to the fact that the soil reclamator is self-propelled and functions without the need to involve a heavy tractor. The mathematical modeling of the operation of the proposed technical support for the treatment of waste heap reclamation in comparison with the opposed analog proves the ecological and economic efficiency of the eco-adaptive soil reclamator. The average value of profit ratios, when using the proposed soil reclamator, is 121.82 % higher than with the involvement of opposed equipment. Indicators of the negative environmental impact of the designed equipment are 100 % lower than the environmental impact when operating the analog. The proposed technical solution can be effectively applied both in schemes of sanitary cleaning of settlements, and in the process of modernization of agricultural machinery

Keywords: reclamation, machine degradation, tilled furrow, ecological and economic efficiency, eco-adaptive soil reclamator, mine waste

Received date 24.03.2022
Accepted date 17.08.2022
Published date 30.08.2022

***How to Cite:** Baikalov, Y., Dzhygyrey, I., Bendiuh, V., Proskurnin, O., Berezenko, K., Boichenko, S., Kryuchkov, A., Serhiienko, M., Danilin, O., Kutniashenko, O. (2022). Improvement of quarry and slagheap reclamation technology. Eastern-European Journal of Enterprise Technologies, 4 (10 (118)), 38–50. doi: https://doi.org/10.15587/1729-4061.2022.263513*

1. Introduction

Every year the amount of damaged fertile land in the world gradually increases [1]. This is especially true of the territories of those countries that direct their economies to the development of the agro-technical complex, and which play an important role in the world food market.

The modern view of the agro-industrial and ecological state of a number of countries in the world as a whole shows an unpromising situation, which in the coming years will require considerable attention and scientific and technical improvement of existing approaches. Thus, military activities violate the existing agro-ecological infrastructure around the world, causing a global food crisis [2]. It should be noted that the problem of providing the population with food under conditions of irrational distribution of resources has long remained an issue that required much more attention [3]. And under the conditions of military blocking of food supplies, destruction of agricultural infrastructure and damage to agricultural territories become even larger.

The overall efficiency of agricultural production is determined by the rational use of land resources, the sustainable development of means of labor, and the peculiarities of their use when using the natural resource potential [3]. Given this, the introduction of the latest equipment and, accordingly, approaches to reclamation and development of new agricultural areas is an important scientific task. In addition, the improvement of the existing land reclamation and reclamation systems will allow speeding up the restoration of damaged ecosystems.

As far as the reclamation of agro-landscape areas is concerned, the least studied technologies are those related the restoration of areas damaged as a result of mining and industrial activities [4]. For example, in Ukraine, in areas with developed mining production, a huge number of waste dumps and quarries have been formed today, thereby disabling significant areas of fertile land. In the Donetsk oblast alone, there are about 600 heaps ranging from 4 to 1400 thousand m^2 each [5], and the total area of dumps of mining enterprises of the Lviv-Volyn coal basin exceeds 250 hectares [6]. The vast majority of these man-made relief forms, about 80 %, are no longer used by industries, and are promising areas for development. Therefore, given the urgent need to restore the agricultural industry of Ukraine [2], research on improving the equipment for slope reclamation of various natural-technogenic and man-made relief forms is extremely relevant.

2. Literature review and problem statement

The issue of reclamation of territories damaged by mining enterprises has been raised for a long time. Both quarries and heaps cause significant damage to both the environment and the economy of the state [7]. Therefore, today in world practice there is a whole range of measures that are aimed at restoring and improving the natural conditions of man-made-disturbed territories [8].

A significant part of scientific studies tackling the issue of restoration of mining and industrial areas considers the main solution to the environmental problem to be the filling or flooding of quarries [9], as well as disassembling waste dumps with their subsequent use [10]. However, according to their author, such approaches do not contribute to the restoration of ecosystems and the renewal of damaged soils.

A promising direction that will significantly reduce the negative impact of man-made landscape facilities on the environment, while obtaining a positive economic effect, is the reclamation and treatment of disturbed areas [11].

Much attention in current scientific works on the reclamation of anthropogenically damaged areas is paid to the selection and evaluation of the relevant flora and fauna [12], climatic factors [13], and chemical indicators of soils [11] of a certain renewable area. Comprehensive reclamation measures, according to the authors of [14], should include strengthening of soils in vulnerable areas by hydro-sowing of a mixture of soil improvers, geosynthetic coating, and anti-erosion planting on subhorizontal (angle of inclination $<2°$) and slope (angle of inclination $>2°$) surfaces, etc.

At the same time, minimal attention is paid directly to technologies and equipment for reclamation and treatment of slopes of man-made relief forms. However, the current growth rate of relevance in the issue of shortage of fertile land and, as a result, the global food crisis [2], in recent years, has been increasingly pushing the horizons of scientific directions of this complex problem.

Thus, a study into the features of the reclamation of landscapes damaged during the extraction of minerals is reported in [15]. The study focuses on the view that there are no clear requirements for the reclamation and alignment of anthropogenic relief. This generally complicates the processing of sloped land plots [16]. The paper investigates the influence of slope angles, quarry depth, and other characteristics of degraded landscapes on the choice of land reclamation methods. However, the authors almost did not study the influence of the landscape characteristics of the site on the work of existing land reclamation equipment, which is mostly not adapted to work on the slopes.

Soil reclamation in slope areas is discussed in detail in [17], which considers the processing of Sicilian vineyards. The structural basis of the reclamation equipment there is a disc plow in combination with a swing tractor. As a result of research into the treatment of slope areas with such equipment, it was found that such tillage can redistribute the soil up the slope, and opens up new opportunities for the use of such equipment for the sustainable management of crops. However, among the shortcomings of the technology proposed in the work, it is worth noting the direct dependence of its effectiveness on the skills of the operator and significant energy costs (about 3 kW/ha) due to the use of even a mini-gripping machine-tractor unit in difficult areas [18].

The problems of reclamation of slope lands with the use of heavy agricultural equipment were also considered in [19]. In particular, one of the tasks of the work was to assess the impact of slopes and the direction of tillage on erosion caused by the transportation of the upper fertile layer by agricultural equipment during reclamation. As a result of research, it was found that erosion during tillage with a dump plow [20] may increase due to the greater depth of reclamation and the high speed of the equipment. These results are applicable to determine targeted measures to reduce soil loss and maintain its fertility. At the same time, despite the indication of obvious shortcomings of the existing arable equipmen, the work does not provide alternative equipment designs for effective reclamation of natural-technogenic soil relief forms.

The possibilities of improving existing structures for the treatment of damaged areas are also considered by the authors of [21]. After analyzing all the major drawbacks of traditional soil reclamators, such as complex and inefficient transmission systems, high fuel consumption, and high exhaust emissions, the authors devised a promising solution. A method for designing systems of a hybrid electric drive of a soil reclamator by calculating its rated thrust was proposed. Such a soil reclamator best adapts to different working conditions and possesses increased traction characteristics. The power of the electric motor of such a device meets the requirements for working conditions with an increased load. However, the large-scale implementation of such technology is difficult in many countrie, including in terms of profitability of this tillage technique.

Analyzing the world experience, it should be recognized that theoverwhelming majority of classical examples of industry equipment existing in modern agriculture today do not have the technical ability to adapt to work in areas of anthropogenic relief while not significantly changing the basic structure. Even minimal design variations significantly affect their overall effectiveness. Therefore, it was concluded that in order to solve the scientific and technical problem under consideration, it is necessary to use non-standard equipment that is not yet used on an industrial scale but can effectively process various areas of natural and man-made soil relief forms.

The literary review of soil reclamators, a variety of structures and configurations that were designed in many countries in different years [22], once again testifies to the permanent relevance of reclamation of complex landscape areas and anthropogenically damaged areas. Thus, the design of the device for reclamation and restoration of soil fertility damaged by the mining industry is considered in [23]. Unlike classical structures, the presented unit for plowing and rotary tillage is able to loosen the soil and prepare it for sowing in one operation, which, due to the smaller number of «runs», makes it possible to preserve the fertile soil layer more effectively. However, despite certain technical advantages, the design presented by the authors is not considered under the conditions of performing operations on mountainous terrain.

In [24], the difficulties directly related to the problem of using tillage units on the slopes, as well as under conditions of complex microrelief and the presence of obstacles in the working area are considered in detail. According to the authors, one of the biggest issues is an uncontrolled change in the trajectory of the soil reclamator. Unlike standard solutions, such as increasing overall stability with the help of additional directional working bodies or the creation of multi-link mechanisms [25], the work proposes the use of automatic biometric adjustments of control systems. However, despite the high adaptive capabilities of the proposed equipment, the implementation of such a solution in Ukraine on an industrial scale today seems impossible due to the high cost and complexity of non-standard equipment, as well as the need for additional training of highly qualified operators. In addition, such equipment still needs to be operated in conjunction with a tractor.

Taking into consideration the reviewed world experience related to the issue of reclamation of complex landscape areas and anthropogenically damaged areas, it can be noted that the main difficulties in the processing of man-made landscape facilities are:

– the high weight of equipment that causes slipping and disruption of the fertile soil layer;

– the high energy consumption of equipment due to reduced cross-country capacity of the terrain and the use of additional machine and tractor units;

– the impossibility of adapting existing technologies to the features of the relief;

– additional costs for the training of qualified operators.

3. The aim and objectives of the study

The aim of this study is to improve the technology of reducing the machine degradation of soils in the mining reclamation of quarries and waste heaps with the possibility of use for the processing of agricultural land. The practical use of the research results will make it possible to include the developed technical solution for the modernization of technical support of sanitary cleaning schemes for settlements by increasing the efficiency of restoring the fertility of the surfaces of mine waste dumps and manufactured quarries.

To accomplish the aim, the following tasks have been set:

– to design universal technical support for the reclamation of complex landscape areas and anthropogenically damaged areas;

– to conduct a simulation of ecological and economic efficiency of the proposed technical solutions to improve the reclamation process.

4. The study materials and methods

The object of this research is the technical support of mining reclamation of quarries and the surface of waste heaps.

The working hypothesis assumed the possibility of effective replacement of soil reclamators with the traditional design of the power plant by a reclamation device with a pneumatic-gravitational drive and the ability to reduce the machine degradation of the fertile layer during the processing of a heterogeneous landscape.

The theoretical design of equipment for the reclamation of heaps involved methods for developing technical solutions according to the theory of solving inventive problems [26].

Underlying the modeling of ecological and economic efficiency of the introduction of the designed equipment for terracing heaps is the use of a well-known methodology for modeling the effectiveness of specialized technical support [27]. The selected system of mathematical expressions makes it possible to choose equipment, its optimal composition and long-term functioning mode, using a simulation mathematical model for calculating annual and final indices of ecological and economic efficiency. The model includes the following system of mathematical expressions (1), which determine the procedure for implementing the modeling methodology [27–29]:

$$\left.\begin{array}{l} x_1=(x_4+x_5)\cdot h_1\cdot h^{2365D}/h_3, \\ x_6=(F_1-F_2)/h^{21095D}, \\ x_2=(x_6+x_7)\cdot h_1\cdot h^{2365D}, \\ x_3=(Z_1+Z_2+Z_3+Z_4)\cdot h_1\cdot h^{2365D}, \\ Y_1=\sum X_1/T, \\ Y_2=\left(\left(\sum X_2-\sum X_3\right)-\%W\right)/T, \end{array}\right\} \quad (1)$$

where x_1 is the index of environmental effect (coefficient of emissions of pollutants per 1 ton of processed waste by the sum of units of equipment per year), (log index – (conditional numerical value of the estimated characteristics of the object));

x_2 is the index of economic effect (profit ratio per 1 ton of processed waste per year), (log index);

x_3 is the index of technical and economic effect (coefficient of expenditure of funds per 1 ton of processed waste per year), (log index);

x_4 is the release of pollutants into the atmospheric air from a unit of equipment indexed (g/h);

x_5 is the discharge of pollutants into the hydrosphere from the unit of equipment indexed (g/h);

x_6 is the hourly profit from an indexed unit of equipment (UAH/hour);

x_7 is the total market value of functions (commercial cost of providing services on request) (UAH/hour);

h_1 – the number of operated units of equipment indexed (units);

h^{2365D} – the number of hours of operation of a unit of equipment indexed per year (hour/ year);

h^{21095D} – the number of hours of operation of an indexed unit of equipment over a constant period (3 years), (hour/year);

h_3 – the amount of processed waste by the total number of units of equipment indexed (t/year);

F_1 is the cash flow from the operation of a unit of indexed equipment over a constant period (direct profit from the sale of waste processing products, for example, alternative fuel from recycled car tires (conditionally 3 years)), (UAH/year);

F_2 is the cost (or cost upon purchase) of a unit of equipment indexed (for the first year of forecasting) (in subsequent years – the cost of new units, when updating the fleet of equipment, or value 0, in the absence of costs) (UAH/year);

Z_1 is the remuneration of personnel required for the operation of a unit of equipment (UAH/hour);

Z_2 – the cost of the area occupied by a unit of equipment indexed (based on the average cost of renting 1 sq. m. of industrial sites and taking into consideration the dimensions of the unit of equipment) (UAH/hour);

Z_3 – the cost of energy resources that are consumed during the operation of the indexed unit of equipment (UAH/hour);

Z_4 – the cost of troubleshooting the projected problems and maintenance $NR_i = e_{i0} / e_{coni}$, of the indexed equipment unit over a period of 1 year (per hour of operation of the equipment unit) (UAH/hour);

Y_1 – the final index of the environmental effect (the average value of the impact of equipment on the environment per 1 ton of treated waste in the forecast period) (log index);

Y_2 is the final index of economic effect (average profit from equipment per year per 1 ton of processed waste in the forecast period), (log index);

$\sum X_1$ – the sum of annual indices X_1 for the forecast period;

$\sum X_2$ – the sum of annual indices X_2 for the forecast period;

$\sum X_3$ – the sum of annual indices X_3 for the forecast period;

$\%W$ is the projected average percentage of inflation in the region during the forecast period (%);

T – duration of the forecast period (number of years).

Calculations for the specified system of equations are performed using the software «Index-E» [28].

5. Results of improvement and justification of the effectiveness of the technology of reclamation of damaged soils

5. 1. Environmentally adaptive soil reclamator

Solving the totality of the identified components of the investigated problem requires the creation of a balanced technical solution, environmentally adapted to the peculiarities of the conditions of its functioning according to different types of hard-to-reach areas without changing the design of technological equipment. The developed apparatus "Ecoadaptive soil reclamator" (Fig. 1) refers to the mining industry and agricultural machinery, namely to machines for agrotechnical work using a combined pneumatic gravitational power unit for transporting agricultural tools. The basic structure of the soil reclamator includes a double-walled housing containing a cylinder with a built-in spring, a turbine with an electric generator. The generator is connected to the battery using a cable, a coupling case rigidly connected to a hinge to which the folding bridge is attached (Fig. 2). The bridge is equipped with one or more wheels, bottom-tip, having one or more rollers for transporting the unit. According to the technology of eco-adaptive soil reclamation, the design of a removable controlling element for irrigation and fertilization of the soil can additionally be used. The element can be equipped with a piezo-driven exhaust valve containing a supporting frame, the tank with an inclined drain bottom connected to it by means of reinforcing supports is filled with a liquid biologically active substance (Fig. 3). The device may provide a seat, made in the form of a seat for the operator of the device.

The ecoadaptive soil reclamator can also additionally contain a removable gravitational pneumohydraulic circular irrigation generator, rigidly installed on the outer surface of the upper base of the cylinder, and having a cylindrical body shape (Fig. 4, 5). The generator contains a cylindrical piston tank coaxially installed in it with the formation of interwall space. The tank includes a cylindrical spring rigidly fixed on its lower base, which is connected to a disc-shaped piston, with the possibility of its reciprocating movement inside the piston tank. In the interwall space there is an annular piston, which, with the possibility of its reciprocating motion, is fixed on a cylindrical spring. The upper base of the dynamic cylinder is connected to the turbine power generating unit using a pipe equipped with an automatic one-way valve and an internal nozzle. The turbine is equipped with an exhaust pipe, which is connected with a watering pipe fixed on a telescopic folding bridge by connecting to sprayers, with the ability to rotate along the vertical axis of the hinge. The electric generator of the turbine unit is electrically connected by an electrical wire to the battery of the pump-accumulator unit, the pump of which is connected to the filling pipe entering the piston cylinder and equipped with a tap. The lower base of the housing and piston cylinder are rigidly connected to the mounting plate, which is equipped with two valve pipes equipped with double-sided valves. The pipes connect the piston cylinder and the interwall space to the generator turbine-battery compartment containing a turbine electric generator rigidly and electrically connected to the battery. The energy storage device has an electrical connection to the electroaccumulator of the pump-battery unit through an electrical wire.

The eco-adaptive soil reclamator can be equipped with a towing device to connect it to a vehicle, an additional pair of wheels, and can be easily delivered to a new place of operation. The device may also contain a transport electric motor connected to the motor-wheels, powered from batteries. Batteries are part of the base unit, using their excess charge of electricity generated by the elements of the device. The electric motor may be powered by an additionally installed solar panel. The device can also be equipped with a steering mechanism, which makes the technological complex mobile and self-propelled.

One or more additional folding bridges can be connected to the coupling hull of the soil reclamator to secure more controlling elements on them. This makes it possible to implement several types of operations simultaneously during the work of one small-sized unit of equipment.

The key structural elements of the designed equipment and schemes of options for its use under different conditions are shown in Fig. 1–8. The basic version of the eco-adaptive soil reclamator when performing technological processes of mining reclamation of disturbed soils or in the implementation of various agricultural works on the processing of agricultural areas, functions as follows. After installing the proposed unit in the central part of the planned work site, the device (Fig. 1) is fixed by natural penetration of bottom-tip 8 into the soil.

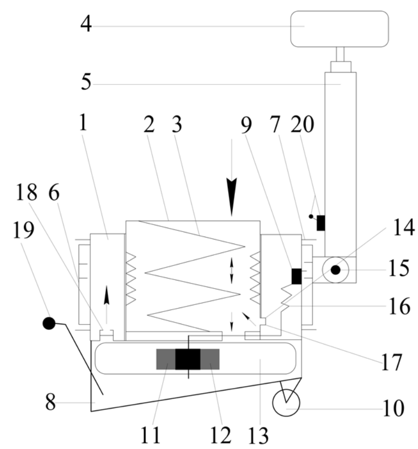


Fig. 1. Schematic diagram of the apparatus "Ecoadaptive soil reclamator" in the static state: 1 – double-walled cylindrical housing; 2 – pneumatic cylinder; 3 – cylindrical spring; 4 – running wheel; 5 – bridge; 6 – coupling housing; 7 – limiter; 8 – bottom; 9 – battery; 10 – transport roller; 11–12 – generator; 13 – blades; 14 – drive pipe; 15 – hinge; 16 – cable; 17 – return pipe; 18 – intermediate connection pipe; 19 – operator's handle; 20 – control joystick

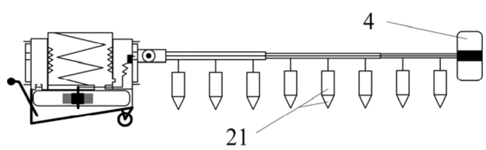


Fig. 2. Scheme of ecoadaptive soil reclamator in dynamic state: 4 – running wheel; 21 – controlling element

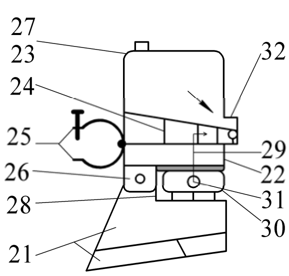


Fig. 3. Scheme of a removable actuator for irrigation and fertilization of the soil with a piezo-driven releasing valve: 21–22 – the body of the controlling element; 23 – tank with inclined drain bottom; 24 – reinforcing supports; 25 – fastener; 26 – hinge connection; 27 – inlet for filling the tank with an inclined drain bottom; 28 – spikes-deformers; 29 – piezo-driven electrical cable; 30 – piezocrystalline element, 31 – electrode; 32 – exhaust pipe

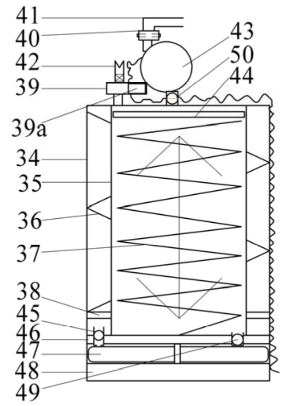


Fig. 4. Scheme of gravitational pneumohydraulic circular irrigation generator: 34 – cylindrical housing; 35 – piston tank; 36 – spiral spring; 37 – cylindrical spring; 38 – ring piston; 39 – pump; 39a – battery; 40 – pipe hinge; 41 – irrigation pipe; 42 – filling pipe; 43 – turbine; 44 – piston; 45, 49 – drive pipes; 46 – mounting plate; 47 – electric generator; 48 – electric accumulator; 50 – valve pipe

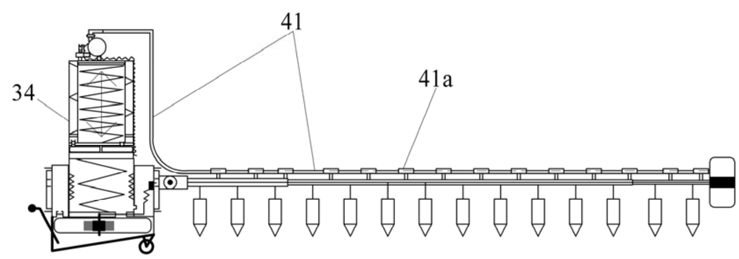


Fig. 5. Connection diagram of the gravitational pneumohydraulic generator with the base apparatus: 41a – sprayer

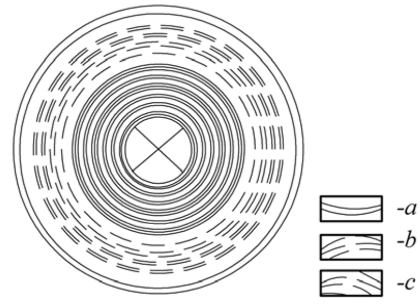


Fig. 6. Scheme of the exploited area of agricultural soils during its circular processing (in combination with the implementation of care for agricultural plants): *a* – edging furrow from the passage of the drive wheel; *b* – tilled furrow; *c* – area of other tillage or plants; *d* – location of the base device

After the described operations, energy-generating manipulations are carried out, including the implementation of a gravitational effect on the upper base of cylinder 2, by vertically placing the operator, standing (or by sitting taking into consideration the presence of a seat) on it. Next, cylinder 2 and spring 3 are compressed, which entails the volumetric displacement of compressed air from cylinder 2, through pipe 14 (possibly equipped with a modification of the Loval nozzle) into the lower compartment. This drives the electric generator 11–12 into operational motion by jet action on its blades (Fig. 1). Next, as it is injected into the compartment, air through valve pipe 18 enters the interwall space of housing 1, where it accumulates. The pulse produced by the electric generator is transmitted via cable 16 battery 9, where it accumulates with the possibility of further consumption of electricity. After the maximum compression of cylinder 2, the gravitational effect of the operator on it is stopped, which entails the automatic restoration of its shape by unclenching spring 3. In this case, the compressed gas medium is reversed from the interwall space of housing 1 to cylinder 2 through a pipe equipped with one-way valve 17. Further or in advance, the operator enables the operational position of bridge 5 by straightening it in hinge assembly 15. After that, the sections of the bridge are extended to the desired length, which is equal to the radius of the plot of land to be cultivated (Fig. 2, 6). After that, by switching control joystick 20, engine 4a and wheel 4 are brought into working condition, followed by a circular movement of suspended actuators 21 previously connected to bridge 5. When switching joystick 20, the "On" state is supplied with electricity from battery 9 to the wheel electric motor, through a cable passing inside the empty sections of bridge 5, which causes the drive wheel to start rotating. Due to the circular trolley groove of the power transmission located on the inner surface of the rotating coupling housing 6, the power supply of the power element of wheel 4 is maintained when housing 6 rotates. Then there is the movement of bridge 5, and the circular transportation of controlling elements 21, which is the reason for the implementation of complex agrotechnical processing and mining reclamation of territories. The operation of the proposed design of the controlling element of the eco-adaptive soil reclamator is as follows. In the process of towing bodies with bridge 5, for example, a tilled action occurs, carried out by the plow part of element 21. This entails its narrow-amplitude motion in connection 26, compression of the piezoelectric element 30 with spikes 28, and the generation of an electrical pulse by the occurrence of a piezoelectric effect. Next, the electric current is induced by electrode 31 and it is transmitted using electrical wire 29 to the electric drive valve located in exhaust pipe 32 (Fig. 3). When processing the top layer of soil with plow 21, a metered discharge of a liquid biologically active substance (fertilizer) from tank 23 into the arable furrow in parallel with the plowing process itself under the energy autonomous mode can be performed. Fertilization can be carried out in the process of sowing plants, provided that the corresponding filler is filled into tank 23.

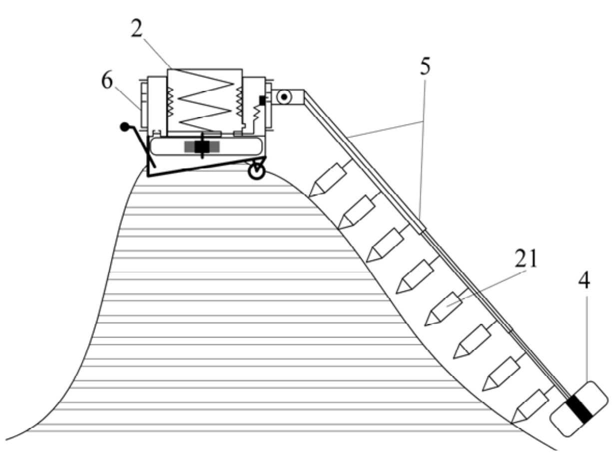


Fig. 7. Layout of the soil reclamator during the processing of hills and heaps: 2 — pneumatic cylinder; 4 — running wheel; 5 — bridge; 6 — coupling housing; 21 — controlling element

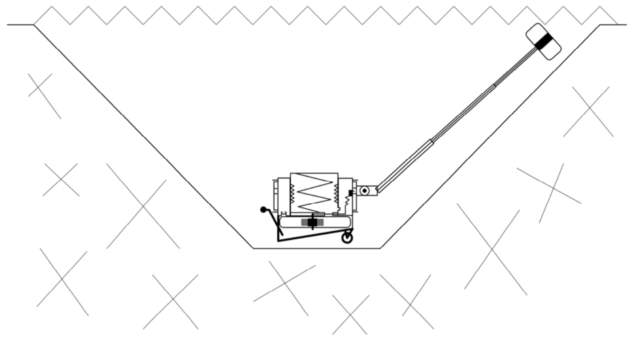


Fig. 8. The layout of the soil reclamator when processing quarries

Other agricultural devices and devices aimed at performing various agricultural or reclamation works can be connected to bridge 5. At the same time, several different types of work can be performed simultaneously (for example, plowing the soil and watering already growing plants). This is done by placing various equipment on bridge 5, with varying degrees of removal of the bridge from rotating housing 6. In addition, weights can be attached to bridge 5 in order to obtain sufficient force, for example, for plowing. Using a wide range of hinged movement of bridge 5, the unit can be used to treat soils located at different angles of inclination relative to the location of the unit itself. When choosing the desired position of the bridge and fixing the position of hinge 15, the device can be operated in various processes of processing the slopes of hills, when terracing heaps (Fig. 7), mining reclamation of quarry slopes (Fig. 8). It is possible to use the designed apparatus even during agrotechnical work in areas with a heterogeneous landscape, without fixing the position of hinge 15 and the angle of inclination of bridge 5.

The operation of the gravitational pneumohydraulic circular irrigation generator (Fig. 4) as part of the unit (Fig. 5) begins with its installation on the upper base of cylinder 2. Pipe 42 at the same time with the help of a flexible stretchable hose can be connected to any nearest water source. The device can use a centralized water supply system, a natural or artificial reservoir, a water generator of any design that is able to synthesize water at the place of operation of the unit, etc. Next, manually, automatically or remotely, the valve in pipe 42 opens, unit 39–39a is turned on, water enters the upper part of the piston cylinder, the weight of which acts on piston 44 by compressing spring 37. This leads to the movement of compressed air from the space under piston 44 (which is pumped once at the stage of preparing the installation for operation) through pipe 49, by mechanically opening the two-way valve. Further, the compressed air, acting on the blades of turbine 47, starts the generation of electricity and its accumulation by battery 48. In this case, the valve in pipe 45 opens, the interwall space is filled with air, which affects piston 38, raising it and compressing spring 36, spring 3 in cylinder 2 in the main unit. This starts the generation and accumulation of electricity there.

With a maximum filling of cylinder 35 with water, springs 36 and 37 are completely compressed, the valve in pipe 50 is opened manually, automatically, or remotely, the tap in pipe 42 is closed. This entails the displacement of water from cylinder 35 through pipe 42, the jet effect of water on the turbine blades of unit 43, the generation of electricity in it and its accumulation by battery 39a. The accumulated energy is used for the operation of pump 39, with further cycles of operation of the device for supplying water to the device. Getting into pipe 41, water fills it along the entire length of bridge 5, is distributed over sprayers 41a, and irrigates the working area during the circular movement of bridge 5. When this occurs, springs 36 and 37 are unclenched, piston 44 is raised, piston 38 is lowered, the air is reversed through pipes 45 and 49 into cylinder 35, with the background operation of turbine 47. This is accompanied by the accumulation of the received electricity in battery 48.

In parallel, as the weight of the generator decreases, cylinder 2 is unclenched, and spring 3 in the main unit. The cycle repeats. The accumulated excess electricity can be used to move bridge 5 or to transport the device to a new location. The frequency and sequence of operation of the taps and valves of the device can be represented in the form of a program code and controlled using a computer remotely. This makes it possible to automate the operation of the entire device without significant changes in its basic design. Irrigation of the territory can be carried out continuously under a given mode, excluding the human factor in the management of the process. Humidification can be combined with the implementation of various processes of processing the territory, by simultaneous installation with pipes 41, 41a, sprayers with other mounted actuators on bridge 5. After performing the work, the device can be returned to a static state and transported to the place of its storage even in small utility rooms.

The design of the proposed soil reclamator has a pronounced ability to adapt to different working conditions (to different types of landscape of disturbed soils) due to the wide range of possible angle of inclination of the traction bridge, without machine degradation of the soil.

The above description of the technology of eco-adaptive reclamation gives grounds for conducting simulation mathematical modeling of long-term operation of the proposed equipment. A comprehensive substantiation of the ecological and economic efficiency of the introduction of the device under the conditions of reclamation of small waste heaps is a necessary prerequisite for the use of technology in the period of post-war ecological restoration of the territory of the Ukrainian Donbas.

5. 2. Modeling the ecological and economic efficiency of equipment using the technology of eco-adaptive soil reclamation

Given the revealed lack of profitable, under the economic conditions of developing countries, analogs of the designed soil reclamator, when evaluating it, the device under ideal conditions, it is advisable to contrast the popular equipment – a rotary plow. The ability to perform a self-propelled version of the developed device makes it mandatory when modeling its effectiveness, taking into consideration the cost of a tractor necessary for the operation of any plow. Thus, the equipment to achieve high efficiency of the process can be the rotary plow "Falc Freeland 4000" (country of origin: Italy) and the tractor "John Deere 8430" (country of origin: USA) with the required capacity for the plow of 300 hp. The technical characteristics of these units of equipment, even at the stage of choosing analogs, gives ample reason to consider their use economically viable. However, the analysis of the technology of application of such heavy equipment on the slopes of mine dumps (especially in relation to newly formed small waste heaps) proves the presence of a number of probable environmental risks. Among the man-made consequences of such an application of this complex with a total weight of 14119 kg (with fuel), it is important to highlight the pollination of air by toxic fine particles of rocks ground by the wheels of the tractor, displacement of the fertile layer of thericon. It is also possible to destroy the internal structure of the dump, which can have unpredictable environmental consequences. The lack of accurate scientifically confirmed data on the power of all negative man-made processes makes it impossible to objectively model the environmental efficiency of the equipment and contrast it with the designed apparatus for their comparative ecological and economic assessment.

Environmental safety of surface treatment of mine dumps requires the use of light, energy-saving, self-propelled technical support with competitive productivity. However, the modern level of technology can hardly effectively meet this need. With this in mind, as an analog, which is opposed to the designed eco-adaptive soil reclamator, a well-known, but somewhat outdated, patented "device for preparing the surface of waste heaps for landscaping" was chosen. The equipment includes a frame, an internal combustion motor, a screw working body, a wheel reducer, a chain drive. The device has a bracket on which the worm gearbox is fixed, the rotation of which is carried out through a chain drive, the drive sprocket of which is located on the same line as the bracket mount [30]. The device performs the function of terracing and digging holes and provides for the need for constant monitoring of its work by the operator, without the possibility of automatic and energy-saving mode of operation.

In accordance with the chosen methodology for forecasting the ecological and economic efficiency of long-term operation of specialized technical support [27–29] in the process of automated calculation of the mathematical model, the conditional dynamics of mutually dependent values of equipment parameters were taken into consideration. Possible socio-economic, technical, and political changes in the region of the planned use of the technical solution were taken into consideration.

In addition, the formation of the initial data scenario for modeling is based on the task of implementing a conditional long-term project of preparation for terracing, landscaping, and further work on complex agrotechnical reclamation of coal mine heaps. We conventionally accepted a possibility of commercial sale of grown agricultural products on 30 small heaps.

For convenience of calculations, modular parameters of dumps are also conditionally accepted. The module is based on the heap of the Pionerka mine (Donetsk, Ukraine):

– height=11 m;
– base area=3830 m^2;
– volume of waste=14 thousand tons; m^2;
– amount of waste=25.2 thousand tons; t;
– conical, does not burn, out of operation.

On a sufficiently formed fertile layer of slopes of dumps, with the help of the designed apparatus, wheat crops or vegetable raw materials for the production of fuel briquettes and biofuels can be grown. The processes of sowing, caring for plants (for example, watering crops and fertilizing the land), and harvesting can be carried out using the proposed device under the mode of its energy-autonomous, round-the-clock automatic operation. When modeling a long-term waste heap processing project, the profit from the sale of the obtained products on a modular dump in the amount of USD 3000 per year is conditionally accepted. A direct dependence of the amount of profit on the degree of need to attract leased third-party equipment to obtain a sufficient amount of products has been adopted. Such additional equipment can be technical support of the processes of sowing plants, their watering and harvesting.

Additionally, when forming the task for modeling, the following factors were conditionally accepted:

– bank lending of the initial purchase of equipment (for 3 years, at a total rate of 10 %);

– partial updating of the technical support of the project (purchase of several units of equipment on years 14–15 of the project implementation, in the amount of 30 % of the initial total cost of equipment);

– preferential cost of renting an industrial site for conditionally possible storage of design equipment in relation to the developed eco-adaptive reclamation;

– subsidized financing of repair work on energy-saving technologies;

– an increase in energy prices in the world;

– an increase in the minimum wage;

– an increase in prices for industrial raw materials;

– projected average inflation is 15 % (subtracted from the value of the total profit ratio with a long-term forecast).

The initial data on the eco-adaptive soil reclamator and the contrasted equipment of the terracing technology of waste heaps, with their corrections for 15 years for the calculation of performance indices, are given in Tables 1, 2.

Table 1

Initial data for calculation in the software «Index-E» («Device for preparing the surface of waste heaps for landscaping» [30] (conditionally, 264 (22 days/month) operator work shifts/year, 8 hours each) — «Plug 1») according to the procedure from [27–29]

Parameter name	Dimensionality	Initial values	Value correction (No. 1)		Value correction (No. 2)		Value correction (No. 3)		Value correction (No. 4)		Value correction (No. 5)	
			%	year	%	year	%	year	%	year	%	year
Emission power (per unit of equipment) when burning 14 kg ICE gasoline	g/h	505	No**	No	No	No	No	No	No	No	No	No
Discharge power (per unit of equipment)	g/h	0	No	No	No	No	No	No	No	No	No	No
Cost of functions (unit of equipment)	a.u.*/hour	33	+20	4	+35	6	+60	8	+100	10	110	12
Number of equipment units	unit	70	No	No	No	No	No	No	No	No	No	No
Hours of work	hours/year	2,112	No	No	No	No	No	No	No	No	No	No
Working hours (3 years)	hours/year	6,336	No	No	No	No	No	No	No	No	No	No
The amount of processing waste	tons/year	420,000	No	No	No	No	No	No	No	No	No	No
Zp. personnel (per unit of equipment)	a.u./hour	4	+40	3	+70	5	+100	8	+120	10	140	14
Cost of space (per unit of equipment)	a.u./hour	0.06	+50	5	+100	10	+150	15	No	No	No	No
Cost of energy resources (per unit of equipment)	a.u./hour	42.68	+40	3	+70	5	+100	7	+120	10	+200	13
Repair cost (per unit of equipment)	a.u./hour	0.71	+30	4	+50	6	+80	8	+100	10	+150	14
Cash flow (per unit of equipment)	a.u./year	1,000	+50	3	+100	7	+150	10	+200	13	+250	15
Cost (per unit of equipment)	a.u./year	5,000	–60	1	–60	2	–70	3	–100	4	–70	14

*Note: * a.u. – USD; no** – no correction of the initial values*

Table 2

Initial data for calculation in the software «Index-E» (eco-adaptive reclamation under the round-the-clock automatic mode of operation with irrigation (conditionally, 300 days of work/year (25 days/month)) — «Plug 2») according to the procedure from [27–29]

Parameter name	Dimansionality	Initial values	Value correction (No. 1)		Value correction (No. 2)		Value correction (No. 3)		Value correction (No. 4)		Value correction (No. 5)	
			%	year	%	year	%	year	%	year	%	year
1	2	3	4	5	6	7	8	9	10	11	12	13
Emission power (per unit of equipment)	g/h	0	No**	No	No	No	No	No	No	No	No	No
Discharge power (per unit of equipment)	g/h	0	No	No	No	No	No	No	No	No	No	No
Cost of functions (unit of equipment)	a.u.*/hour	70	+20	4	+45	6	+75	8	+120	10	200	13
Number of equipment units	unit	30	No	No	No	No	No	No	No	No	No	No
Hours of work	hours/year	7,200	No	No	No	No	No	No	No	No	No	No
Working hours (3 years)	hours/year	21,600	No	No	No	No	No	No	No	No	No	No
The amount of processing waste	tons/year	420,000	No	No	No	No	No	No	No	No	No	No
Zp. personnel (per unit of equipment)	a.u./hour	1.5	+40	3	+70	5	+100	8	+120	11	140	14
Cost of space (per unit of equipment)	a.u./hour	0.06	+50	5	+30	7	+10	10	–20	11	–40	14

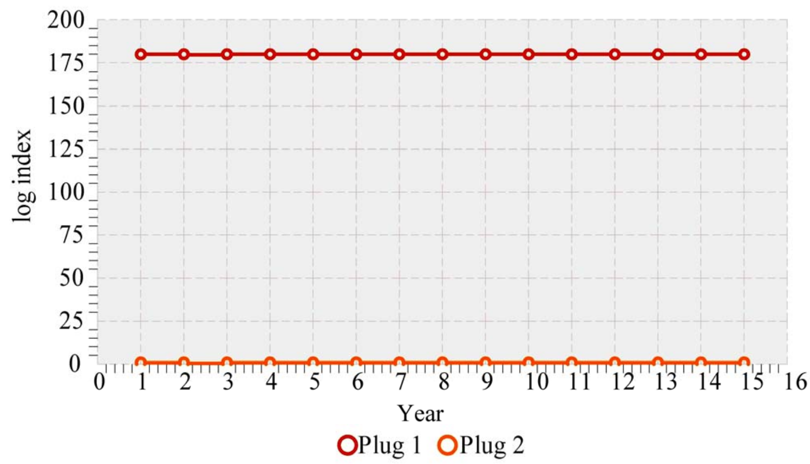
Continuation of Table 2

1	2	3	4	5	6	7	8	9	10	11	12	13
Cost of energy resources (per unit of equipment)	a.u./hour	0	No	No	No	No	No	No	No	No	No	No
Repair cost (per unit of equipment)	a.u./hour	0.42	No	No	No	No	No	No	No	No	No	No
Cash flow (per unit of equipment)	a.u./year	3,000	+50	3	+100	7	+150	10	+200	13	+250	15
Cost (per unit of equipment)	a.u./year	10,000	–60	1	–60	2	–70	3	–100	4	–70	14

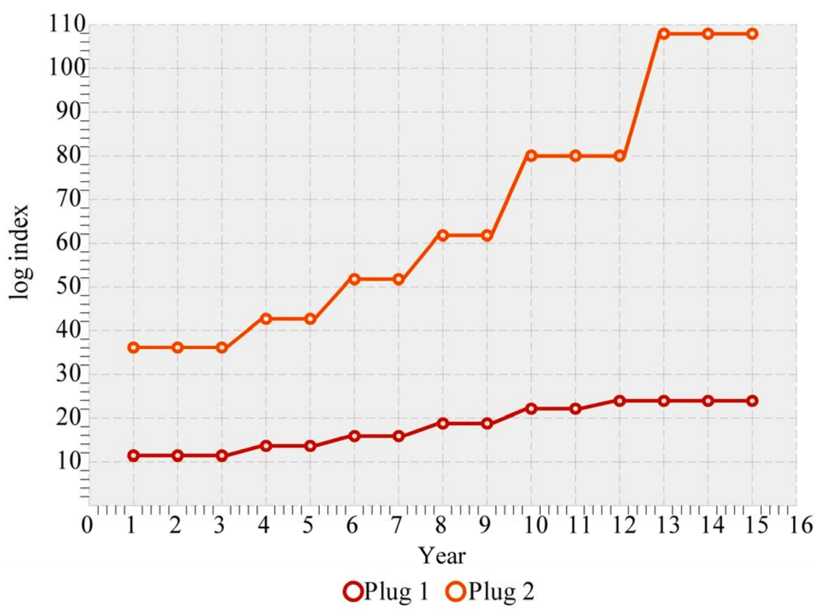
*Note: * a.u. – USD; no** – no correction of the initial values*

According to the results of the calculation in the software «Index-E», taking into consideration the above data from Tables 1, 2, we visualized annual and final ecological and economic indices for the studied objects (Fig. 9, 10).

Our results are a sufficient basis for a comprehensive justification of the choice of specialized equipment for the process of reclamation of the surface of slagheaps and the formation of practical recommendations for increasing its efficiency

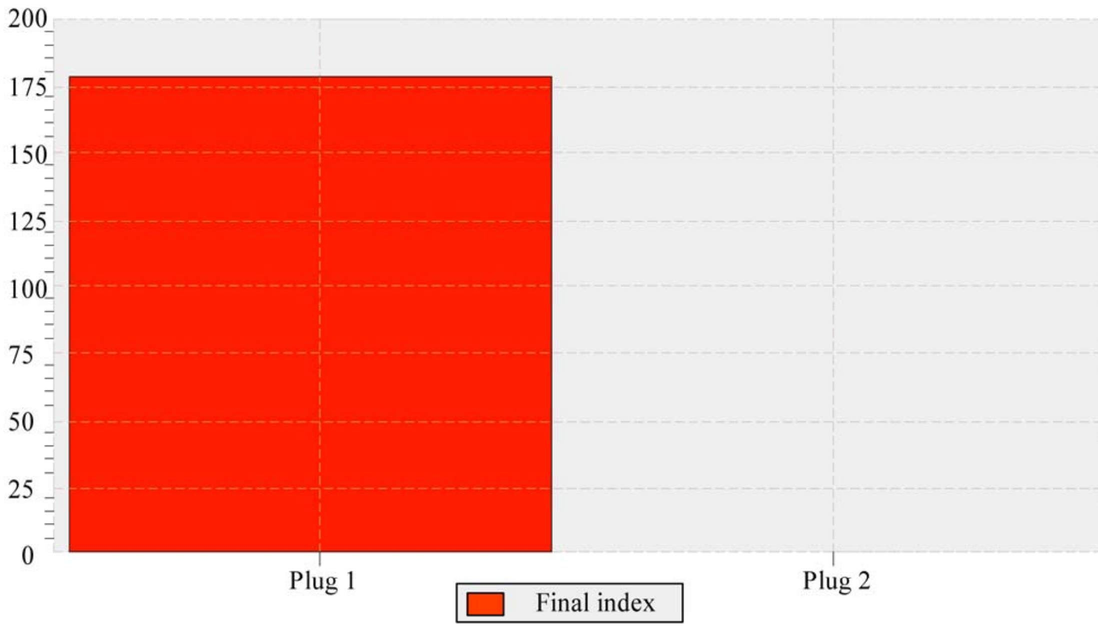


a

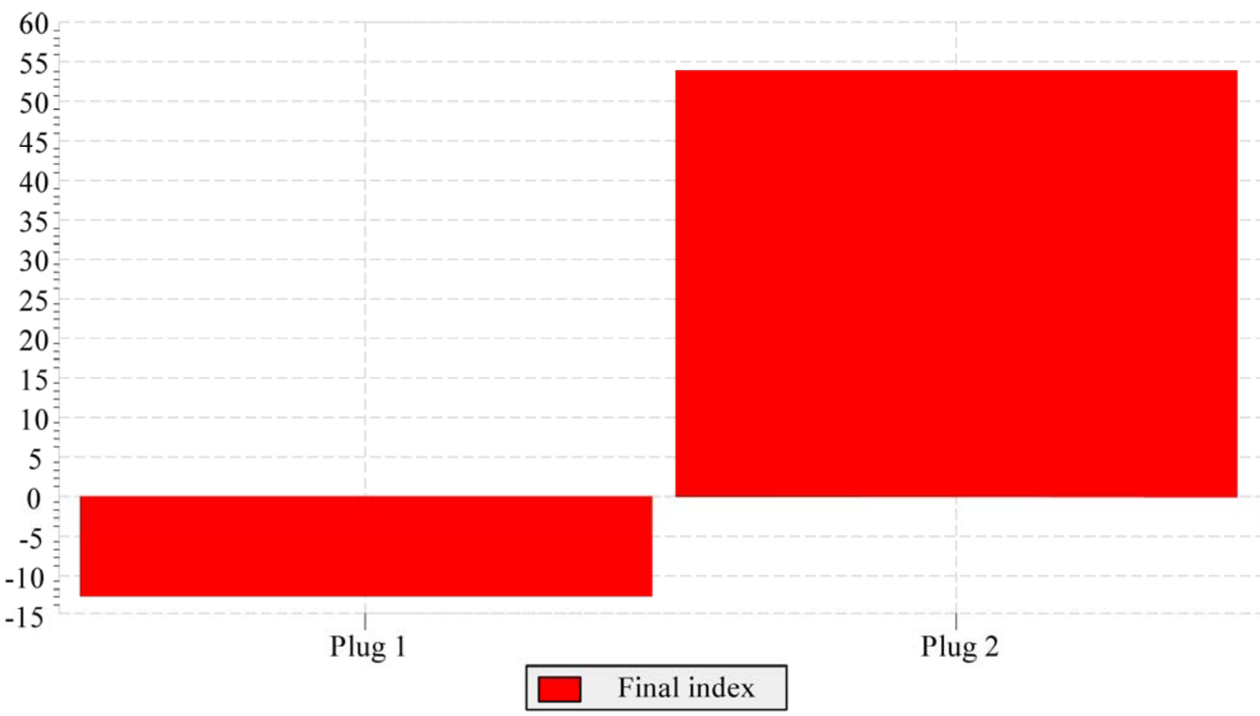


b

Fig. 10. Results of the calculation of the final indices of environmental "a" and economic "b" effects (taking into consideration the projected inflation of 15 %) of the objects studied in the forecast period (the value of the coefficients of profit and impact of equipment on the environment per 1 ton of processed waste):
a – results of the calculation of the final environmental index;
b – results of the calculation of the final economic index



a



b

Fig. 9. Dynamics of annual indices: *a* – environmental anti-effect (loss) from objects studied during the forecast period (coefficients of emissions of pollutants per 1 ton of recycled waste with a total number of pieces of equipment per year) according to the project; *b* – economic effect of the objects studied in the forecast period (profit ratio per 1 ton of processed waste per year)

6. Discussion of results of the improvement and justification of the effectiveness of the technology of reclamation of disturbed soils

The technical result of the considered technology is expressed in ensuring the possibility of carrying out various processes of mining reclamation of waste heaps and quarries with a significant reduction in the level of environmental risks by operating energy-saving small-sized, multifunctional equipment (Fig. 1–8). The use of the designed soil reclamator is also adequate for pre-sowing and other types of agrotechnical tillage, plant care (for example, for irrigation) in agricultural fields, as well as in areas with a heterogeneous landscape. The functionality of the unit is able to provide energy autonomy and automation of the technological process. The low weight of the device makes it possible to minimize the pressure on the soil, which reduces the environmentally hazardous formation of dust during the treatment of waste heaps, the destruction of its structure, the machine degradation of the fertile layer during the processing of all types of territories. The device also reduces the risk of fertile soils slipping from the slopes of mine dumps due to the fact that the soil reclamator is self-propelled and functions without the need to involve a heavy tractor. This indicates the prospect of effective use of the technical solution both in the schemes of sanitary cleaning of settlements and in the process of modernization of agricultural machinery. All this is an advantage of this study relative to, for example, works [9, 21–22].

Analysis of the modern level of technology did not reveal direct analogs of the proposed soil reclamator according to its basic characteristics. The closest modern technical support for technological tasks is a multifunctional device [23]. However, in order to reduce the technogenic load on the fertile layer, if it is possible to simultaneously perform agro-technical processes, the device does not provide for its operation in a heterogeneous landscape, unlike the eco-adaptive soil reclamator.

The designed equipment makes it possible not to use traditional engines in agricultural works, the operation of which is reported in [23], which increases efficiency and practically eliminates air pollution when using the proposed device. The disadvantage of the opposed technical support is the very limited width of the coverage area, which it covers with one "run", while the proposed development makes it possible to cover almost the entire surface of a small heap for a "run". The combination of these differences makes it incorrect to select this soil reclamator as a full-fledged analog of the presented technical solution. This makes it possible to choose an analog from earlier developments, which is a device for preparing the surface of waste heaps for landscaping [30].

The simulation mathematical modeling (1) of long-term operation (Tables 1, 2) of the proposed technical support of the processes of processing the reclamation of waste heaps in comparison with the opposed analog proves the ecological and economic efficiency of the eco-adaptive soil reclamator. The value of profit ratios, when implementing a conditional project (a.u./ton of waste in mine dumps) using the proposed soil reclamator (Plug 2), is 121.82 % higher than with the involvement of opposed equipment (Plug 1). The device from [30] under modern conditions is economically unprofitable, as evidenced by the negative number of the profit indicator (Fig. 11, *b*). At the same time, the analysis of the annual values of this indicator (according to Plug 2) shows a confident trend of its stable growth, while with analog equipment it is expressed very weakly (Fig. 10, *b*). Indicators of the negative environmental impact of the developed equipment are 100 % lower than the environmental impact when operating the opposed analog (Fig. 10, *a*, *b*).

The limitations of this study are in the generalization of the described procedure and hardware settings in the process of using the soil reclamator, which may require clarification, taking into consideration the conditions of the practical operation of the designed device.

The disadvantage of our study is the lack of results of practical tests of the «pilot» sample of the designed equipment, which are planned to be the next stage of work on the introduction of eco-adaptive reclamation technology for disturbed soils.

The main promising directions and planned stages of development of the study are:

– improvement of the design of the telescopic bridge of the soil reclamator;

– optimization selection of materials for the implementaa tion of structural elements of the developed equipment;

– improvement of the design of the controlling element in order to maximize the set of its functions, possible for implementation to perform all the necessary modern reclamation and agricultural types of soil treatment;

– development of software that controls the automatic mode of operation of the eco-adaptive soil reclamator;

– increasing the ecological and economic indicators of the use of an eco-adaptive soil reclamator by optimizing and analyzing scenarios for its implementation during repeated simulation of mathematical modeling.

7. Conclusions

1. The designed technical support makes it possible to carry out various processes of mining reclamation of waste heaps and quarries with a significant reduction in the level of environmental risks through the operation of energy-saving small-sized, multifunctional equipment. The use of the developed soil reclamator is also adequate for pre-sowing and other types of agrotechnical tillage, plant care (for example, for irrigation) in agricultural fields, as well as in areas with a heterogeneous landscape. The functionality of the unit is able to provide energy autonomy and automation of the technological process. The low weight of the device makes it possible to minimize the pressure on the soil, which reduces the environmentally hazardous formation of dust during the treatment of waste heaps, the destruction of its structure, the machine degradation of the fertile layer during the processing of all types of territories. The device also reduces the risk of fertile soils slipping from the slopes of mine dumps due to the fact that the soil reclamator is self-propelled and functions without the need to involve a heavy tractor. This indicates the prospect of effective use of the technical solution both in the schemes of sanitary cleaning of settlements and in the process of modernization of agricultural machinery.

2. The simulation mathematical modeling of long-term operation of the proposed technical support of the processes of processing the reclamation of waste heaps in comparison with the opposed analog proves the ecological and economic efficiency of the eco-adaptive soil reclamator. Thus, the average value of profit ratios, when implementing a conditional project using the proposed soil reclamator, is 121.82 % higher than with the involvement of opposed equipment. The device under modern conditions is economically unprofitable, as evidenced by the negative number of the profit indicator. At the same time, the analysis of the annual values of this indicator shows a confident trend of its stable growth, while with analog equipment this is very weakly expressed. Indicators of the negative environmental impact of the developed equipment are 100 % lower than the environmental impact when operating the opposed analog due to the absence of emissions of pollutants during

the operation of the developed equipment. The design of the proposed soil reclamator has a pronounced ability to adapt to different working conditions (to different types of landscape of disturbed soils) due to the wide range of possible angle of inclination of the traction bridge, without machine degradation of the soil.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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