https://doi.org/10.33271/nvngu/2026-2/076

B. I. Stepaniuk[*],
orcid.org/0009-0000-2415-079X,
O. P. Lukyanchuk,
orcid.org/0000-0002-0892-545X,
O. V. Iliuchok,
orcid.org/0009-0009-0239-4668

National University of Water and Environmental Engineering, Rivne, Ukraine
[*] Corresponding author e-mail: b.i.stepaniuk@nuwm.edu.ua

JUSTIFICATION OF A RATIONAL SCHEME FOR CONFIGURING SOIL-TREATING MACHINERY

Purpose. The purpose of this study is to determine the most effective method for configuring multi-element working equipment in order to ensure minimum traction forces during the development of deposits located close to the earth's surface.

Methodology. Analytical methods for calculating cutting forces of the soil environment by soil-developing working bodies, 3D computer modeling and analysis methods using CAD software, and experimental research methods were employed.

Findings. It has been established that modifying the spatial configuration of cutting elements, as opposed to a conventional row layout, results in a substantial reduction in traction forces and an enhancement in equipment productivity. For working bodies without asymmetrical block cutting, the most effective arrangements in terms of reducing traction forces are angular, V-shaped, Δ-shaped, and mirrored checkerboard arrangements. For equipment with asymmetrical block cutting, angular, checkerboard, Δ-shaped, and trapezoidal arrangements are most effective. Research has demonstrated that optimizing the geometric parameters of cutting elements in the subcritical cutting region ($b/h = 0.25$–1) yields the most significant outcomes, including a reduction in traction force of up to 37 % and an enhancement in productivity of up to 31 %. As the b/h ratio increases, the effectiveness of optimization decreases, and at $b/h > 4$, it becomes ineffective.

Originality. For the first time, the present study comprehensively established the influence of spatial layout, number (3–10), and geometric parameters of cutting elements on the energy and productivity indicators of multi-element soil excavation equipment. This was achieved by taking cutting modes into account, and the limits of optimization efficiency for the ratio (b/h) were substantiated.

Practical value. The findings of this study can be utilized in the design and modernization of soil excavation equipment, with the objective of reducing energy costs, enhancing productivity, and optimizing the efficiency of machine operation.

Keywords: *deposit development, cutting elements, cutting conditions, layout, reduced effort, energy efficiency*

Introduction. Mechanical engineering is an important industry in Ukraine, specializing in the design, production, and use of machines and equipment.

In most developed countries around the world, among self-propelled and towed equipment of various purposes – from underwater devices to spacecraft – earthmoving machinery occupies a primary position.

Earthworks are among the most labor-intensive processes in construction, mining and agricultural activities. It is therefore important to develop ways to improve the designs of earthmoving machines based on a techno-economic analysis of their various models.

The scientific and technical foundations for the creation of any machinery are based on the use of advanced, high-speed and energy-efficient technologies and machines designed to operate in both natural and artificial environments under various conditions. This encompasses a wide range of terrestrial activities, including road construction, mineral deposit development, agricultural land cultivation, engineering-military and rescue operations, soil cleaning, land reclamation, irrigation, trench and canal excavation, earthworks, and shelter creation. It also includes underground activities, such as the extraction of minerals and other industries.

During the operation of an earthmoving machine, most of the energy is spent on overcoming the forces that arise during soil digging by the working body, soil transportation along the working body, and its filling. The main disadvantages of passive working bodies include excessive energy consumption of the working process, soil compaction along the walls of the cut slots, and insufficient quality and completeness of loosening. At the same time, reducing the cutting force is possible in some cases with minor design modifications and low material costs by changing the interaction conditions of the working equipment with the soil environment – from blocked and asymmetrically blocked to less energy-intensive semi-blocked and free.

Literature review. To address the identified problems of soil-working machinery, scientific articles presenting the results of relevant studies were analyzed.

Paper [1] introduces a pulverization (fracture) model that relies on the physical and mechanical behavior of soil during interaction with a wedge-shaped tool, rather than on soil elasticity. This theoretical framework shows closer alignment with experimental results compared to models based on elastic assumptions. Its validity was further confirmed through tests of flat tillage implements operating with adjustable cutting angles.

Paper [2] presents the results of research aimed at improving the efficiency of trench excavation for utility line installation by employing new, energy-efficient soil excavation techniques in multi-scraper excavators. The study identifies optimal operating conditions for these trench excavators, as well as recommended dimensions for their lateral cutting blades, providing guidance for enhancing the design and overall performance of this type of equipment.

Research [3] applied an analytical method to determine the arrangement parameters of soil-working elements and to evaluate the energy efficiency of a trench excavator's multi-scraper chain, based on a semi-blocked soil cutting regime at critical depth.

In [4] study, a numerical model based on cohesive elements was developed to investigate the dynamic rock-breaking process and mechanisms under compound impact.

Study [5] explored three different pick arrangements to identify the optimal configuration for a bolter miner's cutting head. The performance of each configuration was thoroughly assessed under varying rotational speeds using both numerical simulations and experimental testing.

The paper [6] studied cutting performance of the cutting drum under two working modes and various cutting thickness, including the load, working power and specific energy. The research results indicate that the arrangement of conical picks on the cutting drum is suitable for sequential arrangement of single-headed spiral lines in hard rock strata. These findings have a significant reference value for the design of the cutting drum.

Paper [7] investigates how rock fractures under the action of a cutting pick, taking into account its mechanical properties and relevant parameters. The study analyzes rock fragmentation processes and the impact of different cutter spacings on breakage efficiency. Experiments were carried out using a rotary cutting device with a single pick at various cutting depths and cutter spacings. The insights from the analysis of rock failure and cutter spacing optimization offer guidance for understanding rock-breaking mechanisms in roadheaders and for improving pick layout design.

In paper [8], in order to study the rock-breaking mechanism of compound impact drilling, the thermal-structure coupling simulation of the dynamic rock-breaking process with a single PDC cutter was investigated by using ABAQUS software. The influence of impact parameters on the rock-breaking performance and cutting temperature was analyzed. The results proved that the compound impact load changes the rock failure mode and improves the rock-breaking efficiency.

In paper [9], the effect of blade geometry and rotary speed on furrow formation during rotary strip tillage was investigated. The study analyzed key furrow parameters, including depth, width, and shape, as well as soil displacement characteristics in the cutting zone. The findings of the study demonstrated that variations in blade design and rotational speed significantly influence the quality and efficiency of the rotary strip tillage process.

Paper [10] substantiated the initial and boundary conditions for the functioning of the model and found the ratio of the physical and mechanical properties of the soil and the viscosity of the medium. The results of determining the traction resistance of the tool and their comparison with the results obtained during laboratory experiments on the soil channel are presented. The proposed method of modeling the soil treatment allows you to analyze the power characteristics of the working bodies and the quality of the soil at the design stage of tillage machines. The obtained characteristics make it possible to optimize the structural and technological parameters of the working bodies of machines on the computer.

In study [11], discrete element method (DEM) simulations were used to assess how variations in tine rake angle, forward speed, working depth, and depth-to-width (*d*/*w*) ratio affect draught and vertical forces. The simulation findings were compared with experimental measurements for validation. The analysis showed that higher travel speeds, larger tine rake angles, increased working depth, and greater (*d*/*w*) ratios all contributed to increases in both draught and vertical forces.

Papers [12, 13] explore the use of finite element analysis to study the interaction between a cutting blade and soil. The soil is treated as an elastic–plastic medium described by the non-associated Drucker–Prager model. The work introduces a technique for simulating how soil separates during cutting and provides a systematic method for determining the forces applied to the blade.

In [14], an approach to predicting the parameters of precise deep soil loosening based on an analytical model and the discrete element method (DEM) was developed and verified. The models were evaluated based on the findings of experimental studies conducted in a soil channel, thereby enabling the assessment of the accuracy of predicting cutting forces and alterations to the soil profile during deep tillage. It has been demonstrated that DEM modelling provides a superior correlation with experimental data in comparison to the analytical method, thereby confirming its efficacy for analyzing the interaction of the working body with the soil.

Paper [15] describes the development of mathematical models aimed at identifying the critical cutting depth for the outer lateral teeth of multi-slip chains used in trench excavators. The models consider scenarios involving asymmetric side cutting and semi-block cutting of soil.

The paper [16] describes the process of obtaining a dependence for determining the length of the plowshare at the critical cutting depth of the cutters, which allows for the determination of their cutting resistance.

In paper [17], analytical models of soil cutting by the working bodies of earthmoving machines were investigated. The mechanism of interaction of factors influencing the operating process of a machine for exposing (excavating) underground pipelines was examined.

The research [18] investigated the interaction between soil and a rotary tiller equipped with commonly used C-type blades to predict the effects of several operational parameters (forward speed, tillage depth, and rotational speed) and field parameters (soil bulk density and moisture content) on power consumption, and to evaluate surface soil mixing through numerical simulation.

The crack propagation and damage distribution of heterogeneous rock impacted by machinery were studied in paper [19]. The results indicate that during tool impact rock breaking, the rock at the impact point mainly experiences compression and shear failure, whereas tensile stress dominates the propagation of rock cracks around the point of impact. Interlayer distribution and boundary layer ambiguity exist in the propagation of stress waves in heterogeneous rocks. The confining pressure primarily suppresses the propagation of internal cracks and damage in rocks, as it influences tensile and shear stresses. The research results provide a theoretical reference for improving the efficiency of rock breaking by mining machinery impact.

Study [20] proposed a predictive approach to evaluate the effects of subsoiler configuration on draught force and soil porosity, grounded in soil dynamics principles and the fourth strength theory. Validation through field trials and discrete element modeling confirmed the model's predictions, with deviations below 5 %. Among the tested layouts, the "W"-type arrangement was chosen for deeper simulation analysis and adjustment of operational parameters. The results from these simulations corresponded closely with the model's forecasts. Further particle flow examination suggested a quadratic dependency linking subsoiler spacing, draught force, and the degree of soil loosening.

Paper [21] investigated deep subsurface tillage performed with chisel-type subsoilers combined with auxiliary components. The study emphasized the need to examine how the design and arrangement of tillage units influence their overall efficiency. The experiments determined the ranges of operational parameters that result in effective soil fragmentation, achieving pulverization levels of 70–75 %. Optimal outcomes were obtained with chisel tine penetration depths of 32–42 cm, spacing of 80–100 cm between tines in a row, 40–55 cm between rows, forward speeds of 8–9.5 km/h, wing depths of 24–27 cm, and the incorporation of two additional elements such as toothed rollers to improve soil treatment.

In article [22], the effectiveness of multi-subsoiler collaboration in improving subsoiling efficiency is demonstrated, while excessive tillage resistance and soil disturbance are shown to increase energy consumption and soil water loss. Based on DEM-simulations and field experiments, six subsoiler types were evaluated. The results indicate that both subsoiler type and spacing have a significant influence on tillage resistance, with the shank type being the dominant factor. The TC-SM configuration with a spacing of 600 mm exhibited the lowest and most stable tillage resistance. The discrepancy between DEM simulation and field measurements did not exceed 10 %, confirming the reliability of the simulation results.

Purpose. Based on experimentally confirmed data on cutting forces under various soil development conditions, obtained through calculation schemes or dependencies of relative cutting force (ΔP), contact area of the side walls (ΔS), or chipped soil volume (ΔV) to the ratio (b/h) for different cutting methods, it is necessary to determine the optimal configuration of multi-element working equipment that requires the least traction force for the development of deposits located closest to the ground surface.

Methodology. For an accurate comparison of the traction force of different designs of multi-element equipment, it is necessary to conduct theoretical studies and confirm them experimentally.

The research is based on our own theoretical studies on determining the force under different cutting conditions [23] and the results of experimental studies [24]. During the experiments to determine the forces under different soil cutting conditions for the ratios ($b/h = 0.25$; 0.5; 1), cutting depth (h = 0.1 m), and cutting angle ($\alpha_{cut} = 30°$), the experimental data were obtained based on the following principle: the forces acting on the test equipment through the lever system are transmitted to a dynamometer, which records the data and sends them to a computer, where the continuous force data flow is recorded. After comparing the results of experimental and theoretical studies (Fig. 1), it was concluded that the theoretical method for determining cutting forces is within the limits of reliability.

It should be noted that:

1. In the asymmetrically blocked variant, a certain volume of soil is compacted into the side wall to a depth (c_1), which depends on the width of the cutting edge (b_1) and the porosity (e_n).

$$\frac{c_1}{b_1}=\frac{2}{e_n}-1,$$

when e_n = 30–50 % → c_1/b_1 = 6.7–3.0 (according to O. P. Posmitukha, ≈6–4, [25]).

The intensity of this compaction varies according to the triangle law, decreasing away from the cutting zone. To take this into account in further calculations, we assume that the soil density in the side wall directly adjacent to the working body will be on average 2 times (soil density without pores) higher than in front of the working body.

2. The results presented are based on the study of static soil destruction (at minimum cutting speed). Taking into account the energy expended on the deformation of the destruction by the shear of the separated soil layer (P_0), as well as on overcoming the inertial forces of the separated elements of the destroyed soil (P_{kin}), the cutting force at a speed (ϑ) is considered as the sum of two components [26]

$$P_\vartheta=\left(P_0+P_{kin.}\right)\cdot\left(1+\frac{\vartheta}{\vartheta_{crit}}\right),$$

where ϑ_{crit} is the critical cutting speed at which the nature of soil destruction changes.

Results. *Determining the optimal placement of multi-element equipment*. Based on the calculations of forces arising under different interaction schemes of the working organs with the soil – blocked, semi-blocked, asymmetrically blocked, and free cutting [23] – a comparison of the total resistance of the working equipment under varying cutting conditions of the elements is carried out. For evaluation purposes, the reference is taken as the total force occurring when the cutting elements are arranged in a line, as in this case they operate under identical (blocked) cutting conditions.

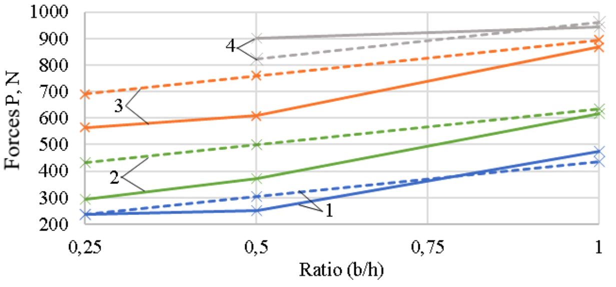

Fig. 1. Dependence of soil cutting force on the ratio of blade width (b) to depth (h) for different cutting methods:

(– – – –) – theoretical data; (———) – experimental data; 1 – free cutting; 2 – semi-blocked cutting; 3 – blocked cutting; 4 – asymmetrically blocked cutting

The initial data for the comparison of the design are taken from the dependence of the relative cutting force (ΔP) on the ratio (b/h) for different cutting methods in hard clay at a cutting depth ($h = 0.1$ m). As a result of the comparisons, Table 1 has been obtained, which shows by how many times the arrangement of cutting elements in a different sequence requires less traction force compared to the arrangement of cutting elements in a row (for relatively narrow ($b/h = 0.25$; 0.5; 1) and relatively wide ($b/h = 2$; 3; 4) cutting elements).

Knowing the force required to break the soil environment, we determine the productivity of the soil breaking process for different ways of arranging multi-element working equipment.

Table 1

Comparison of the total force that occurs in the working equipment for different methods of arranging multi-element working equipment

Relatively narrow cutting elements									Relatively wide cutting elements								
	R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R. T., %		R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R. T., %
For equipment where asymmetric-blocking cutting is absent																	
N	$b/h = 0.25$								N	$b/h = 2$							
3	0	23	27	27	27	23	–	–	3	0	13	14	14	14	13	–	–
4	0	27	27	31	–	–	20	20	4	0	15	15	16	–	–	11	11
5	0	28	30	33	33	30	–	–	5	0	15	16	17	17	16	–	–
6	0	30	30	34	–	–	27	27	6	0	16	16	18	–	–	14	14
7	0	30	31	35	35	33	–	–	7	0	16	17	18	18	18	–	–
8	0	31	31	36	–	–	31	31	8	0	17	17	19	–	–	16	16
9	0	31	32	36	36	35	–	–	9	0	17	17	19	19	18	–	–
10	0	32	32	37	–	–	33	33	10	0	17	17	19	–	–	17	17
N	$b/h = 0.5$								N	$b/h = 3$							
3	0	21	24	24	24	21	–	–	3	0	9	10	10	10	9	–	–
4	0	25	25	28	–	–	18	18	4	0	11	11	12	–	–	8	8
5	0	25	27	29	29	27	–	–	5	0	11	12	12	12	12	–	–
6	0	27	27	31	–	–	24	24	6	0	12	12	13	–	–	10	10
7	0	27	28	31	31	30	–	–	7	0	12	13	13	13	13	–	–
8	0	28	28	32	–	–	28	28	8	0	13	13	13	–	–	12	12
9	0	28	29	33	33	31	–	–	9	0	13	13	14	14	13	–	–
10	0	29	29	33	–	–	29	29	10	0	13	13	14	–	–	12	12
N	$b/h = 1$								N	$b/h = 4$							
3	0	17	20	20	20	17	–	–	3	0	7	8	8	8	7	–	–
4	0	21	21	23	–	–	15	15	4	0	8	8	8	–	–	6	6
5	0	21	23	24	24	23	–	–	5	0	9	9	9	9	9	–	–
6	0	22	22	25	–	–	20	20	6	0	9	9	9	–	–	8	8
7	0	22	24	26	26	25	–	–	7	0	9	9	10	10	10	–	–
8	0	23	23	26	–	–	23	23	8	0	10	10	10	–	–	8	8
9	0	23	24	27	27	26	–	–	9	0	10	10	10	10	10	–	–
10	0	24	24	27	–	–	24	24	10	0	10	10	10	–	–	9	9
For equipment where the extreme side working organs perform asymmetric-blocking cutting																	
N	$b/h = 0.25$								N	$b/h = 2$							
3									3	0	13	0	7	0	13	–	–
4									4	0	9	9	11	–	–	11	0
5									5	0	15	8	13	8	16	–	–
6									6	0	13	13	14	–	–	14	7
7									7	0	16	11	15	12	18	–	–
8									8	0	14	14	16	–	–	16	11
9									9	0	17	13	16	14	18	–	–
10									10	0	15	15	19	–	–	17	13
N	$b/h = 0.5$								N	$b/h = 3$							
3	0	21	0	12	0	21	–	–	3	0	9	0	5	0	9	–	–
4	0	16	16	18	–	–	18	0	4	0	7	7	8	–	–	8	0
5	0	25	13	22	15	27	–	–	5	0	11	6	9	6	12	–	–
6	0	21	21	24	–	–	24	12	6	0	9	9	10	–	–	10	5
7	0	27	18	26	21	30	–	–	7	0	12	8	11	9	13	–	–
8	0	23	23	28	–	–	28	18	8	0	11	11	12	–	–	12	8
9	0	28	21	29	24	31	–	–	9	0	13	9	12	10	13	–	–
10	0	25	25	32	–	–	29	22	10	0	11	11	14	–	–	12	9

Continuation of Table 1

Relatively narrow cutting elements									Relatively wide cutting elements								
	R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R. T., %		R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R. T., %
N	$b/h = 1$								N	$b/h = 4$							
3	0	17	0	10	0	17	–	–	3	0	7	0	4	0	7	–	–
4	0	13	13	15	–	–	15	0	4	0	5	5	6	–	–	6	0
5	0	21	10	18	12	23	–	–	5	0	9	4	7	5	9	–	–
6	0	17	17	20	–	–	20	10	6	0	7	7	8	–	–	8	4
7	0	22	15	22	17	25	–	–	7	0	9	6	8	6	10	–	–
8	0	20	20	23	–	–	23	15	8	0	8	8	8	–	–	8	6
9	0	23	17	23	20	26	–	–	9	0	10	7	9	8	10	–	–
10	0	21	21	27	–	–	24	18	10	0	9	9	11	–	–	–	–

N – the number of working organs; b/h – the ratio of the cutting element width (b) to cutting depth (h) (for asymmetrically blocked cutting, when the ratio (b/h = 0,25), soil development occurs beyond the critical cutting depth, so these data are not considered); R. – arrangement of working organs in a row; S. – arrangement of working organs in a checkerboard pattern; R.S. – arrangement of working organs in an inverse checkerboard pattern; A. – arrangement of working organs at an angle; V – arrangement of working organs in a V – shape; Δ – arrangement of working organs in a delta-shape; T. – arrangement of working organs in a trapezoidal shape; R. T. – arrangement of working organs in an inverse trapezoidal shape; (– – – –) – impossible symmetric arrangement of cutting elements

The energy intensity of soil cutting is equal to the work (A), performed by the soil tillage tool over the cutting length (L), divided by the volume (V) of the destroyed (loosened) soil along this length

$$E_{cut.} = \frac{A}{V} = \frac{P \cdot L}{F_{cut} \cdot L} = \frac{P}{F_{cut}}.$$

Take into account that the cross-sectional area of the trapezoidal cut (F_{cut}) is determined for the blocked and free cutting methods using formula

$$F_{cut} = (b + h \cdot \mathrm{ctg}(\gamma)) \cdot h,$$

while for the semi-blocked and asymmetrically-blocked cutting methods, it is determined using formula

$$F_{cut} = b \cdot h + \frac{(h)^2}{2}\mathrm{ctg}(\gamma).$$

Knowing the cutting force (P), we compare the productivity of the working process for different ways of arranging multi-element working equipment (Fig. 2).

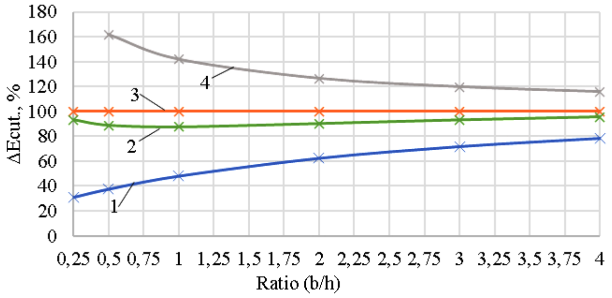

Fig. 2. Dependence of relative energy consumption (ΔE_{cut}) on the ratio (b/h) for different cutting methods:
1 – asymmetrically blocked cutting; 2 – blocked cutting; 3 – semi-blocked cutting; 4 – free cutting

As a result of the comparisons, Table 2 presents how many times the working equipment with the rearrangement of cutting elements in a different sequence is more productive than the working equipment with the cutting elements arranged in a row (for relatively narrow

Table 2

Comparison of productivity for different ways of configuring multi-element working equipment

For equipment where asymmetric-blocking cutting is absent																	
Relatively narrow cutting elements									Relatively wide cutting elements								
	R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R.T., %		R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R.T., %
N	$b/h = 0.25$								N	$b/h = 2$							
3	0	23	5	5	5	23	–	–	3	0	13	7	7	7	13	–	–
4	0	19	19	5	–	–	3	3	4	0	12	12	7	–	–	5	5
5	0	28	17	5	5	17	–	–	5	0	15	11	8	8	11	–	–
6	0	24	24	6	–	–	5	5	6	0	14	14	8	–	–	7	7
7	0	30	22	6	6	14	–	–	7	0	16	14	8	8	11	–	–
8	0	27	27	6	–	–	5	5	8	0	15	15	9	–	–	7	7
9	0	31	25	6	6	12	–	–	9	0	17	15	9	9	11	–	–
10	0	28	28	6	–	–	5	5	10	0	16	16	9	–	–	8	8
N	$b/h = 0.5$								N	$b/h = 3$							
3	0	21	7	7	7	21	–	–	3	0	9	5	5	5	9	–	–
4	0	18	18	8	–	–	6	6	4	0	9	9	5	–	–	3	3
5	0	25	17	9	9	17	–	–	5	0	11	8	5	5	8	–	–
6	0	23	23	9	–	–	7	7	6	0	11	11	6	–	–	5	5
7	0	27	21	10	10	15	–	–	7	0	12	10	6	6	8	–	–

Continuation of Table 2

For equipment where asymmetric-blocking cutting is absent																	
Relatively narrow cutting elements									Relatively wide cutting elements								
	R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R.T., %		R., %	S., %	R.S., %	A., %	V, %	Δ, %	T., %	R.T., %
8	0	25	25	10	–	–	8	8	8	0	11	11	6	–	–	5	5
9	0	28	23	10	10	14	–	–	9	0	13	11	6	6	8	–	–
10	0	26	26	10	–	–	9	9	10	0	12	12	6	–	–	5	5
N	*b*/*h* = 1								N	*b*/*h* = 4							
3	0	17	8	8	8	17	–	–	3	0	7	3	3	3	7	–	–
4	0	16	16	9	–	–	6	6	4	0	7	7	3	–	–	2	2
5	0	21	15	10	10	15	–	–	5	0	9	6	3	3	6	–	–
6	0	19	19	10	–	–	8	8	6	0	8	8	4	–	–	3	3
7	0	22	18	11	11	15	–	–	7	0	9	7	4	4	6	–	–
8	0	21	21	11	–	–	9	9	8	0	9	9	4	–	–	3	3
9	0	23	20	11	11	14	–	–	9	0	10	8	4	4	5	–	–
10	0	22	22	11	–	–	10	10	10	0	9	9	4	–	–	3	3
For equipment where the extreme side working organs perform asymmetric-blocking cutting																	
N	*b*/*h* = 0.25								N	*b*/*h* = 2							
3									3	0	13	0	3	0	13	–	–
4									4	0	9	9	5	–	–	5	0
5									5	0	15	8	6	4	11	–	–
6									6	0	13	13	7	–	–	7	3
7									7	0	16	11	7	6	11	–	–
8									8	0	14	14	7	–	–	7	5
9									9	0	17	13	8	7	11	–	–
10									10	0	15	15	13	–	–	8	6
N	*b*/*h* = 0.5								N	*b*/*h* = 3							
3	0	21	0	4	0	21	–	–	3	0	9	0	2	0	9	–	–
4	0	16	16	6	–	–	6	0	4	0	7	7	3	–	–	3	0
5	0	25	13	7	4	17	–	–	5	0	11	6	4	3	8	–	–
6	0	21	21	7	–	–	7	4	6	0	9	9	5	–	–	5	2
7	0	27	18	8	6	15	–	–	7	0	12	8	5	4	8	–	–
8	0	23	23	8	–	–	8	6	8	0	11	11	5	–	–	5	3
9	0	28	21	9	7	14	–	–	9	0	13	9	5	5	8	–	–
10	0	25	25	21	–	–	9	7	10	0	11	11	9	–	–	5	4
N	*b*/*h* = 1								N	*b*/*h* = 4							
3	0	17	0	4	0	17	–	–	3	0	7	0	1	0	7	–	–
4	0	13	13	6	–	–	6	0	4	0	5	5	2	–	–	2	0
5	0	21	10	8	5	15	–	–	5	0	9	4	3	2	6	–	–
6	0	17	17	8	–	–	8	4	6	0	7	7	3	–	–	3	1
7	0	22	15	9	7	15	–	–	7	0	9	6	3	2	6	–	–
8	0	20	20	9	–	–	9	6	8	0	8	8	3	–	–	3	2
9	0	23	17	10	8	14	–	–	9	0	10	7	3	3	5	–	–
10	0	21	21	18	–	–	10	8	10	0	9	9	7	–	–	3	3

N – the number of working organs; *b*/*h* – the ratio of the cutting element width (*b*) to cutting depth (*h*) ((for asymmetrically blocked cutting, when the ratio (*b*/*h* = 0.25), soil development occurs beyond the critical cutting depth, so these data are not considered); R. – arrangement of working organs in a row; S. – arrangement of working organs in a checkerboard pattern; R.S. – arrangement of working organs in an inverse checkerboard pattern; A. – arrangement of working organs at an angle; V – arrangement of working organs in a V – shape; Δ – arrangement of working organs in a delta-shape; T. – arrangement of working organs in a trapezoidal shape; R.T. – arrangement of working organs in an inverse trapezoidal shape; (– – – –) – impossible symmetric arrangement of cutting elements

(*b*/*h* = 0.25; 0.5; 1) and relatively wide (*b*/*h* = 2; 3; 4) cutting elements).

Conclusions.

1. After analyzing how much less effort is required from the traction machine for the working process when the cutting elements are arranged in a different sequence compared to when they are arranged in a row (Table 1), the following conclusions can be drawn:

1.1. For the equipment where asymmetrically-blocked cutting is not present:

- placement at an angle is advisable for 3; 4; 5; 6; 7; 8; 9; and 10 cutting elements.;
- V – shaped arrangement is effective for 3; 5; 7; 9 cutting elements;
- Δ – shaped arrangement is effective for 7 cutting elements;

- chessboard arrangement is effective for 3 cutting elements;
- chessboard, trapezoidal, and inverted trapezoidal arrangements are not the best options for reducing traction efforts.

1.2. For the equipment where the outer side working organs perform asymmetrically-blocked cutting:

- arranging the cutting elements at an angle is effective for 4; 6; 8; 10 cutting elements;
- chessboard arrangement is effective for 3; 4; 5; 7; 9 cutting elements;
- Δ – shaped arrangement is effective for 3; 5; 7; 9 cutting elements;
- trapezoidal arrangement is effective for 4; 6; 8; 10 cutting elements;
- V – shaped, inverted trapezoidal, and mirror chessboard arrangements are not optimal for reducing traction efforts.

2. The traction force for the soil development process through the arrangement of cutting elements (relatively narrow and relatively wide) in quantities from 3 to 10 at a single soil development level (up to the critical level) when placing the cutting elements in a row can be minimized as follows:

2.1. For the equipment without asymmetrically blocked cutting:

- for relatively narrow cutting elements ($b/h = 0.25–1$): 37 % for ($b/h = 0.25$); 33 % for ($b/h = 0.5$); 27 % for ($b/h = 1$);
- for relatively wide cutting elements ($b/h = 2–4$): 19 % for ($b/h = 2$); 14 % for ($b/h = 3$); 10 % for ($b/h = 4$).

2.2. For the equipment where the outermost working elements perform asymmetrically blocked cutting:

- for relatively narrow cutting elements ($b/h = 0.5–1$): 32 % for ($b/h = 0.5$); 27 % for ($b/h = 1$); for ($b/h = 0.25$) soil development occurs beyond the critical cutting depth, so these data were not considered;
- for relatively wide cutting elements ($b/h = 2–4$): 19 % for ($b/h = 2$); 14 % for ($b/h = 3$); 11 % for ($b/h = 4$).

3. Analyzing the productivity of working equipment with different cutting element arrangements, the following conclusions can be made:

3.1. For the equipment without asymmetrically blocked cutting: staggered of cutting elements is suitable for 3, 4, 5, 6, 7, 8, 9, and 10 elements; Mirrored staggered arrangement is appropriate for 4, 6, 7, 8, 9, and 10 elements; Δ – shaped arrangement is recommended for 3, 5, and 7 elements. These arrangements are the most productive compared to the in-line arrangement.

3.2. For the equipment where the outermost working elements perform asymmetrically blocked cutting: staggered arrangement of cutting elements is suitable for 3, 4, 5, 6, 7, 8, 9, and 10 elements; mirrored staggered arrangement is appropriate for 4, 6, 8, 9, and 10 elements; Δ – shaped arrangement is recommended for 3, 5, and 7 elements. These arrangements are the most productive compared to the in-line arrangement.

4. The productivity of soil-developing equipment can be maximized by arranging relatively narrow cutting elements ($b/h = 0.25 – 1$) and relatively wide cutting elements ($b/h = 2–4$ in quantities ranging from 3 to 10 as follows:

4.1. For the equipment without asymmetrically blocked cutting:

- for relatively narrow cutting elements ($b/h = 0.25–1$): 31 % for ($b/h = 0.25$); 27 % for ($b/h = 0.5$); 23 % for ($b/h = 1$);
- for relatively wide cutting elements ($b/h = 2–4$): 17 % for ($b/h = 2$); 13 % for ($b/h = 3$); 10 % for ($b/h = 4$).

4.2. For the equipment where the outermost working elements perform asymmetrically blocked cutting:

- for relatively narrow cutting elements ($b/h = 0.5–1$): 28 % for ($b/h = 0.5$); 23 % for ($b/h = 1$); for ($b/h = 0.25$), soil excavation occurs at a depth exceeding the critical cutting depth, so this data was not considered;
- for relatively wide cutting elements ($b/h = 2–4$): 17 % for ($b/h = 2$); 13 % for ($b/h = 3$); 10 % for ($b/h = 4$).

5. As the ratio ($b/h > 4$) increases, the effectiveness of changes in cutting conditions to reduce cutting force and enhance equipment productivity significantly decreases. This implies that for the equipment with multi-element working bodies, optimizing the working process becomes less relevant at such high ratio values.

References.

1. Blednykh, V. V., Svechnikov, P. G., & Troyanovskaya, I. P. (2015). Analytical Model of Soil Pulverization and Tillage Tools. *Procedia Engineering, 129*, 69-74. https://doi.org/10.1016/j.proeng.2015.12.010

2. Kravets, S., Suponyev, V., Goponov, A., Kovalevskyi, S., & Koval, A. (2020). Determining efficient operating modes and sizes of blades for multi-scraper trench excavators. *Eastern-European Journal of Enterprise Technologies, 4*(1(106)), 23-28. https://doi.org/10.15587/1729-4061.2020.208957

3. Kravets, S., & Forsiuk, S. (2022). Analytical determination of energy intensity of critical deep cutting of soils by multi-scraper trench excavators. *Technology Audit and Production Reserves, 2*(1(64)), 11-16. https://doi.org/10.15587/2706-5448.2022.257305

4. Wang, W., Liu, G., Li, J., Zha, C., & Lian, W. (2021). Numerical simulation study on rock-breaking process and mechanism of compound impact drilling. *Energy Reports, 7*, 3137-3148. https://doi.org/10.1016/j.egyr.2021.05.040

5. Qiao, S. (2018). Performance evaluation of different pick layouts on bolter miner cutting head. *Journal of Mining Science, 54*(6), 969-978. https://doi.org/10.1134/s106273911806512x

6. Huang, H., & Guan, H. (2025). Design and cutting performance of the cutting drum for shaft boring roadheader. *KSCE Journal of Civil Engineering*, 100277. https://doi.org/10.1016/j.kscej.2025.100277

7. Zhang Q., Han Z., Zhang M., & Zhang J. (2016). Experimental study of breakage mechanisms of rock induced by a pick and associated cutter spacing optimization. *Rock and Soil Mechanics*. Retrieved from https://ytlx.whrsm.ac.cn/EN/10.16285/j.rsm.2016.08.007#1

8. Wang, W., Liu, G., Li, J., Zha, C., Lian, W., & Gao, R. (2021). Numerical investigation on rock-breaking mechanism and cutting temperature of compound percussive drilling with a single PDC cutter. *Energy Science Engineering, 9*(12), 2364-2379. https://doi.org/10.1002/ese3.990

9. Matin, M. A., Fielke, J. M., & Desbiolles, J. M. A. (2014). Furrow parameters in rotary strip-tillage: Effect of blade geometry and rotary speed. *Biosystems Engineering, 118*, 7-15. https://doi.org/10.1016/j.biosystemseng.2013.10.015

10. Mudarisov, S. G., Gabitov, I. I., Lobachevsky, Y. P., Mazitov, N. K., Rakhimov, R. S., Khamaletdinov, R. R., Rakhimov, I. R., ..., & Gareev, R. T. (2019). Modeling the technological process of tillage. *Soil and Tillage Research, 190*, 70-77. https://doi.org/10.1016/j.still.2018.12.004

11. Shahgholı, G., Kanyawı, N., & Kalantarı, D. (2019). Modeling the Effects of Narrow Blade Geometry on Soil Failure Draught and Vertical Forces Using Discrete Element Method. *Yuzuncu Yıl University Journal of Agricultural Sciences, 29*(1), 24-33. https://doi.org/10.29133/yyutbd.429950

12. Armin, A., Fotouhi, R., & Szyszkowski, W. (2014). On the FE modeling of soil–blade interaction in tillage operations. *Finite Elements in Analysis and Design, 92*, 1-11. https://doi.org/10.1016/j.finel.2014.07.004

13. Barr, J. B., Ucgul, M., Desbiolles, J. M. A., & Fielke, J. M. (2018). Simulating the effect of rake angle on narrow opener performance with the discrete element method. *Biosystems Engineering, 171*, 1-15. https://doi.org/10.1016/j.biosystemseng.2018.04.013

14. Makange, N. R., Ji, C., Nyalala, I., Sunusi, I. I., & Opiyo, S. (2021). Prediction of precise subsoiling based on analytical method, discrete element simulation and experimental data from soil bin. *Scientific Reports, 11*(1). https://doi.org/10.1038/s41598-021-90682-w

15. Kravets, S. V., Lukianchuk, O. P., Kosiak, O. V., & Gaponov, O. O. (2020). Determination of critical depth of cutting soil by cutters with building excavators. *Lecture notes in civil engineering*, (pp. 631-640). Springer International Publishing. https://doi.org/10.1007/978-3-030-42939-3_62

16. Kravec, S. V., Bundza, O. Z., Suponyev, V. N., & Gaponov, O. O. (2020). Determination of the length of the ploughshare and the intensity of soil cutting by the cutters (teeth) of trench excavators. *Bulletin of Kharkov National Automobile and Highway University, 2*(88), 78. https://doi.org/10.30977/bul.2219-5548.2020.88.2.79

17. Sukach, M. K., & Lysak, S. I. (2009). Analysis of soil cutting process models of a trenching machine. *Mining, Construction, Road and Reclamation Machines*, (74), 60-70. Retrieved from https://repositary.knuba.edu.ua/handle/987654321/8355

18. Mohammadi, M., Karparvarfard, S. H., Razavizadeh, N., Tekeste, M., Moazeni_kalat, A., Nematollahi, M. A., Namjoo, M., & Rostami, M. A. (2025). Simulation of interaction between soil and rotary tiller to predict the power consumption and investigation of surface soil mixing. *Soil and Tillage Research, 252*, 106626. https://doi.org/10.1016/j.still.2025.106626

19. Zhao, H., Jiang, H., Wu, Z., Zhao, D., & Wang, A. (2025). Numerical study on the mechanism of tool impact fragmentation in heterogeneous rock under confining pressure. *Deep Resources Engineering*, 100208. https://doi.org/10.1016/j.deepre.2025.100208

20. Liu, M., Sun, J., Huang, D., Qiao, D., Xiang, M., Feng, W., Fu, D., & Wang, J. (2025). Mechanism analysis of soil disturbance in sodic saline–alkali soil tillage based on mathematical modeling and discrete element simulation. *Agriculture, 15*(17), 1885. https://doi.org/10.3390/agriculture15171885

21. Leshchenko, S., Salo, V., Petrenko, D., Vasylkovskyi, O., & Melnychenko, V. (2023). Research on of the influence of deep tiller parameters and combination of operating parts on soil cultivation efficiency. National Interagency Scientific and Technical Collection of Works. *Design, Production and Exploitation of Agricultural Machines*, (53), 196-208. https://doi.org/10.32515/2414-3820.2023.53.196-208

22. Wang, Y., Lu, C., Fan, J., Zhang, X., Chen, K., Chen, J., & Li, X. (2024). Evaluating the effects of subsoiler type and spacing on tillage resistance and soil conservation with DEM simulation and field experiment. *International Journal of Agricultural and Biological Engineering, 17*(6), 115-123. https://doi.org/10.25165/j.ijabe.20241706.8996

23. Lukianchuk, O. P., & Stepaniuk, B. I. (2025). Determination of the rational composition of soil development equipment according to the construction of 3D-models of soil chip elements. *Bulletin of the National University of Water and Environmental Engineering, 1*(105). https://doi.org/10.31713/vt120241

24. Lukianchuk, O. P., Stepaniuk, B. I., & Forsiuk, S. L. (2024). Experimental study of changes in cutting force depending on soil development conditions. *Bulletin of the National University of Water and Environmental Engineering, 2*(106), 3-12. https://doi.org/10.31713/vt220241

25. Posmituha, A., Kravets, S., Suponyev, V., & Kulazhenko, Y. (2018). Determination of the size of the seal zone and the pressure of the soil on underground communications in the process of deformation of the soil by the wedge tip. *Technology Audit and Production Reserves, 5*(1(43)), 11-16. https://doi.org/10.15587/2312-8372.2018.146626

26. Stepaniuk, B. I., Kholodenko, V., Lukianchuk, O. P., & Kravec, S. V. (2024). Determination of the dynamic law of normal pressure distribution on the frontal (head) plane of the working body for soil development. *Bulletin of the National University of Water and Environmental Engineering, 3*(107), 290-296. https://doi.org/10.31713/vt3202429

Обґрунтування раціональної схеми компонування ґрунторозробного обладнання

Б. І. Степанюк, О. П. Лук'янчук, О. В. Ілючок*

Національний університет водного господарства та природокористування, м. Рівне, Україна

* Автор-кореспондент e-mail: b.i.stepaniuk@nuwm.edu.ua

Мета. Визначення оптимального способу компонування багатоелементного робочого обладнання, що забезпечує мінімальні тягові зусилля під час розробки родовищ, розташованих поблизу поверхні землі.

Методика. Використані аналітичні методи розрахунку зусиль різання ґрунтового середовища ґрунторозробними робочими органами, методи комп'ютерного 3D-моделювання й аналізу у програмах типу САПР, методи експериментальних досліджень.

Результати. Встановлено, що зміна просторової схеми розміщення ріжучих елементів, порівняно із рядним компонуванням, дозволяє суттєво зменшити тягові зусилля й підвищити продуктивність обладнання. Для робочих органів без асиметрично-блокованого різання найбільш ефективними щодо зниження тягових зусиль є кутове, V-подібне, Δ-подібне та дзеркальне шахове розміщення, тоді як для обладнання з асиметрично-блокованим різанням – кутове, шахове, Δ-подібне та трапецієподібне компонування. Показано, що оптимізація геометричних параметрів ріжучих елементів у докритичній області різання ($b/h = 0{,}25–1$) забезпечує максимальний ефект: зменшення тягового зусилля до 37 % і підвищення продуктивності до 31 %. За зростання співвідношення b/h ефективність оптимізації зменшується, а при $b/h > 4$ стає малоефективною.

Наукова новизна. Уперше комплексно встановлено вплив просторового компонування, кількості (3–10) й геометричних параметрів ріжучих елементів на енергетичні та продуктивні показники багатоелементного ґрунторозробного обладнання з урахуванням режимів різання, обґрунтовані межі ефективності оптимізації за співвідношенням (b/h)

Практична значимість. Отримані результати можуть бути використані при проєктуванні й модернізації ґрунторозробного обладнання задля зниження енерговитрат, підвищення продуктивності й ефективності експлуатації машин.

Ключові слова: *розробка родовищ, ріжучі елементи, умови різання, компонування, зниження зусилля, енергоефективність*

The manuscript was submitted 07.09.25.