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Results of experimental studies of cutting soils with spatially oriented knives of blade equipment

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Abstract. To carry out experimental studies of the process of cutting the working environment by spatially oriented blades of blade equipment, the dynamometric stand for registering the force load of the author's design of KNUBA was improved, which allowed to conduct full-fledged experimental studies taking into account all the existing factors of interaction between the working environment and the working body during cutting. The use of soils of III, IV, and V categories is proposed as a working environment. As a result of the studies carried out for the dynamometric stand for recording the force load during the study of the cutting process with a spatially oriented knife, the cutting forces at different angles α of its deviation were analytically determined, which perform the work of destroying and overcoming the soil resistance to cutting. According to the results of theoretical studies, it was found that the limits of the cutting force determined for a natural installation with spatially oriented knives and for a laboratory bench are the same, and the nature of their change is also similar and is related to each other by the similarity coefficient. In order to verify the adequacy of theoretical calculations on the dynamometer bench, experimental studies of cutting the working environment were carried out. In the course of experimental studies, normal and orthogonal forces were measured simultaneously, which perform the work of destruction and overcoming the resistance of the soil to cutting. The experimental studies carried out fully confirm the adequacy of theoretical calculations, and the comparison of theoretical and experimental results of determining the cutting force showed their sufficient convergence and, accordingly, the legitimacy of using analytical expressions in calculating the power parameters of machines with spatially oriented knifes of blade equipment. The values of the cutting forces that perform the work of destroying and overcoming the resistance of the soil to cutting, which were determined theoretically, taking into account the similarity coefficients used in physical modelling for the above laboratory stand for recording cutting forces by spatially oriented knife of blade equipment, are compared with the results of the cutting forces determined experimentally on this stand. The maximum value of the error in determining the cutting force by theoretical and experimental methods on the laboratory stand for recording cutting forces by spatially oriented knife of blade equipment is Δ_{δ}=10,06%.

Key words: oblique cutting, spatially oriented, excavator blade, laboratory stand, experimental studies.

INTRODUCTION

During the operation of earthmoving equipment, its working mechanism interacts with the working environment, destroying and separating it from the massif. The main characteristics of the soil cutting process are geometric, kinematic, force and energy parameters, as well as indicators that determine the physical features of soil destruction and the properties of the soil as an object of interaction, the conditions of interaction between the working tool and the soil, and the design of the working tool [1, 2, 4] .

The peculiarities of the soil cutting process are highly dependent on geometric parameters – thickness, width and area of the cut, as well as on the angles of orientation of the working tool in space [3].

Most calculations of earthmoving equipment blades and teeth (knives) are based on the assumption that their parameters do not change during the interaction of the working tool with the soil.

The change in parameters during the spatially oriented action of the working tool parts has not been studied sufficiently. Therefore, the issues of the theory and practice of cutting soils with spatially oriented knife of blade equipment, disclosure of its physical mechanism require further in-depth study.

RESEARCH ANALYSIS

In order to verify the adequacy of theoretical research, experimental studies are carried out with the subsequent comparative analysis of the results obtained in the course of theoretical and experimental studies.

In paper [5] presents the use of patent documentation sources to determine the relevance of the problem of cutting soils with spatially oriented knives when working with earthmoving machines and further analysis of the proposed technical solutions.

In paper [6] presents the results of analysing the nature of chip formation during frontal and oblique cutting of soils. The working hypothesis of the movement of the blade and spatially oriented knife was formed.

In paper [7] presents the results of building an information model of the process of cutting soils with spatially oriented knives of dynamic action. The bulldozer equipment and its main operational tasks are considered.

In paper [8] discusses the results of a study of the resistances that arise during the operation of a bulldozer in the soil environment and the processes in the drawing prism. This affects the stability and productivity of a bulldozer when performing excavation work. The use of the proposed hypothesis of the movement of spatially oriented knives on a bulldozer blade has shown that when excavating soil at different speed ratios, there is a deviation of the angle of application of the cutting force by an angle α, which in turn affects the geometric interaction of the spatially oriented knife with the working environment. Changing the geometric interaction of the spatially oriented knife with the soil affects the cutting force, which led to the creation of a parametric model of the interaction of spatially oriented knives with the working environment. For different knife configurations and different ratios of the bulldozer speed and the spatially oriented knife movement speed, the model was developed.

In paper [9], approaches were used to create a model for calculating soil cutting forces by spatially oriented working tools of construction machines, The calculation model was created in accordance with the working hypothesis, where the movement of spatially oriented knives moves perpendicular to the blade equipment, at different ratios of the speed of the blade movement and the movement of knives, which creates spatial interaction with the working environment, and the deviation of the application of the full cutting force by an angle α.

In accordance with the working hypothesis, we obtained five plans for the movement of the blade's space-oriented blade. Depending on the plan of movement of the spatially oriented knife, its geometric interaction with the working environment changes and, accordingly, the cutting force changes.

In paper [10], approaches were used to create and computer test a model of an experimental bench for cutting soil with spatially oriented working tools of earthmoving machines used on construction sites. The creation of such a computer model of the experimental setup is due to the need for continuous improvement of existing equipment and the creation of new equipment taking into account existing needs. Using the calculations of soil cutting by spatially oriented earth-moving tools in the form of a dihedral knife of blade equipment, computer study of stress equivalents, the sum of linear displacement, the yield strength factor, the strength factor, and the loss of stability factor was carried out.

In paper [11] considers the creation of a physical model of an installation for cutting soils with a spatially oriented knife of a bulldozer blade for experimental studies. In order to study the process of interaction of the working tool with the working environment, it becomes necessary to conduct experimental studies, for which, as a rule, natural objects of research or their models are used. Physical modelling preserves the physical nature of phenomena, but changes their scale. Using the theory of similarity and physical modelling, the conditions of similarity of the installation for cutting soils with a spatially oriented knife of a bulldozer blade are determined, in which the interaction of the working body and the working environment is described by a power equation taking into account their parameters.

Papers [12, 13] provide a description of the model with the operating conditions, which makes it possible to assess the dynamics of such systems, taking into account the connections between the energy source, intermediate elements, transmission mechanism, and working body.

PURPOSE OF THE ARTICLE

The purpose of this paper is to present the results of experimental studies of soil cutting by spatially oriented knives of the bulldozer blade with further comparative analysis of the results obtained in the course of theoretical research.

RESEARCH RESULTS

For experimental research, natural objects of research and their models are usually used. In a full-scale experiment, the means of experimental research interact directly with the object of research, and in a model experiment - with its modelled prototype. When conducting model experimental research, the model acts as a means of experimental research and a direct object of research. Nowadays, the creation of a natural machine for cutting soils with spatially oriented knives of the blade equipment for the purpose of conducting experimental studies would lead to a significant expenditure of time and money. Taking this into account, a physical model of a machine for cutting soils with spatially oriented knives of the blade equipment was built, which is similar to the natural machine for cutting soils with spatially oriented knives. As a physical model of the installation, taking into account the similarity coefficients and the envisaged research tasks, the dynamometer bench for registering the force load (Fig. 1) of the author's design of KNUBA [17], was modified to study the process of cutting the working environment with spatially oriented knife of the blade, which allowed for full experimental studies taking into account all the existing factors of interaction between the working environment and the working tool during cutting.

The laboratory bench, which allows for dynamometric measurements, has the following structure: a frame on which a strain gauge trolley is mounted on guide beams using rollers, and a drive with a spatially oriented knife of the bulldozer blade is attached to it through the strain gauge beams. The trolley of the laboratory bench is equipped with a lifting and lowering mechanism with a handle that allows you to adjust the cutting depth. The possibility of horizontal and vertical movement of the trolley is provided by a screw-nut transmission, a V-belt transmission with a gear ratio of u = 2,5 and an electric motor with a power of N = 2,5 kW and a rotor speed of n = 980 rpm with a control panel and limit switches.

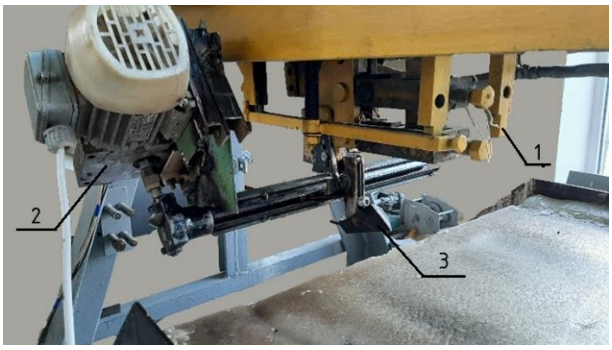

Fig. 1. The model of a spatially orientated knife is fixed in a test bench: *1* – Dynamometer trolley; *2* – The drive of a spatially orientated knife; *3* – Spatially orientated knife

The trolley is equipped with a strain gauge taring mechanism. The hopper with the test material is rigidly fixed to the mounting surface.

The drive for the perpendicular movement of the spatially oriented knife is fixed in the strain gauge trolley.

The movement of the spatially oriented knife, in turn, will be carried out by an engine with a power of N = 1.1 kW and a rotor speed of n = 3000 rpm, through a worm gear, to a bevel gear with a gear ratio, to a screw-nut gear with a total gear ratio u = 8. To test the movement of the spatially orientated knife according

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to the working hypothesis, a marker sticker (Fig. 2) and two model scales were used.

Fig. 2. Place a marker in the centre of the cutting edge

As a test material, a working environment with the physical and mechanical characteristics shown in Table 1 was used.

Table 1. Results

Soil	m_f, MPa	m_s, MPa	$m_{s.c}$, kN/м
Paraffin	0,56	0,022	16,25
Marl clay	0,3	0,021	0,4
Loam	0,15	0,013	1,42
Argillite	0,25	0,024	5,47
Soil	μ	Dimensional characteristics of the fracture zone	
		$k_б$	γ
Paraffin	22°	0,8	36°
Marl clay	14°	0,8	30°
Loam	18°	0,85	40°
Argillite	16°	0,9	30°

The feed rate of the spatially oriented knife into the cutting zone (Fig. 4) was ensured by connecting the drive motor through a frequency converter «Frecon» FR150A.

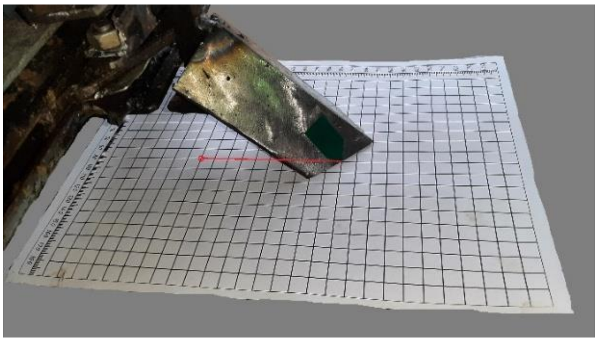


Fig. 3. Verification of the feed rate of a spatially orientated knife using a model scale

In addition, the speed of perpendicular movement of the spatially oriented knife (Fig. 5) was set by connecting the drive motor through a frequency converter «Suswe» T13-750W-12-H.

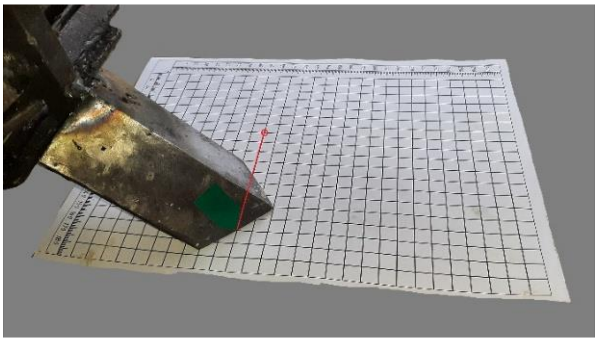


Fig. 4. Verification of the transverse movement speed of a spatially oriented knife using a model scale

Due to the frequency converters, it is possible to change the current frequency of the drive motors, which in turn leads to a change in the speed of movement of the trolley and the spatially oriented knife, which will ensure movement in accordance with the working hypothesis.

To test the angular movement of the spatially oriented knife, a model scale with angular divisions was used, the spatially oriented knife was set to the zero position (Fig. 5) and then launched in accordance with the working hypothesis at different speed ratios (Fig. 6. a, b, c.).

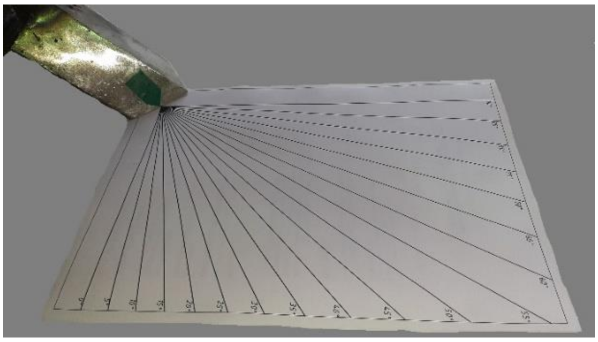
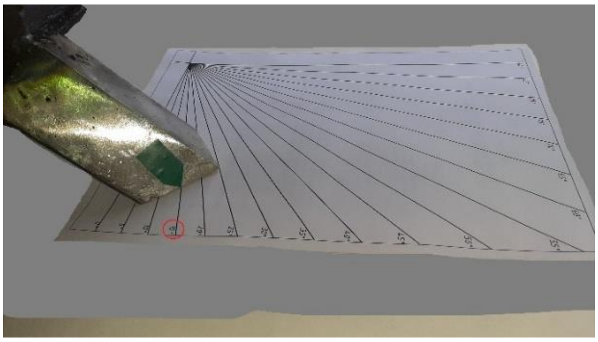
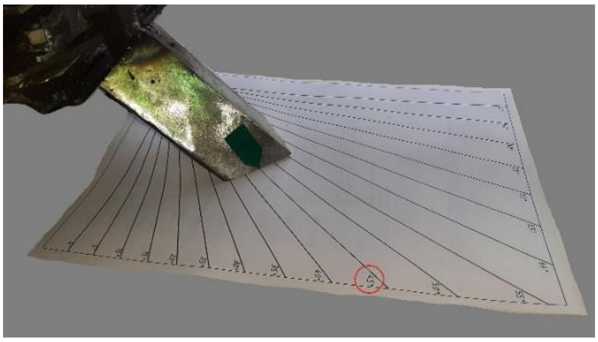


Fig. 5. Setting the spatially oriented knife on the layout scale (With angular divisions, price of divisions 5°)



a



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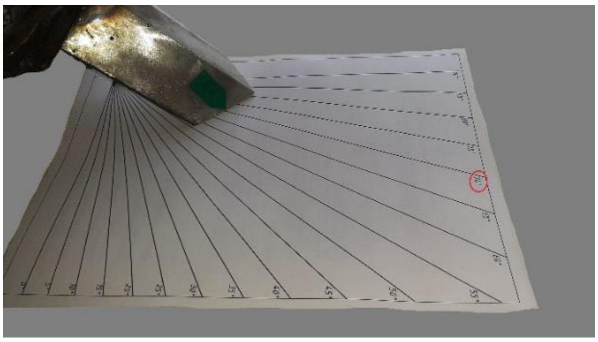

c

Fig. 6. Verification of the angular movement of a spatially oriented knife using a model scale (In terms of angular divisions: a) movement at a speed ratio that ensures α = 15°; b) movement at a speed ratio that ensures α = 45°; c) movement at a speed ratio that ensures α = 70°.)

For the above laboratory bench for recording cutting forces by a spatially oriented knife with the equipment described above, taking into account the similarity coefficients used in physical modelling, the cutting force performed by the cutting and overcoming the resistance of the working medium was determined.

Cutting force of the working environment the spatially oriented knife is described by the equation:

$$P = \varphi(\delta)\varphi_f m_f bh + \varphi_s m_s h^2 + \varphi_{s.c} m_{s.c} h,$$

where b, h – knife width and cutting depth (thickness);

m_f – strength coefficient characterising the specific resistances in the frontal part of the cut;

m_s – strength coefficient characterising the specific resistances in the lateral extensions;

$m_{s.c}$ – strength coefficient characterising the specific resistances along the lateral cut lines;

$\varphi(\delta)$ – coefficient that takes into account the effect of the cutting angle δ (at $\delta = 45^0$ $\varphi = 1$);

φ_f – is a coefficient that takes into account the effect of the angle γ_{pl} of the knife's rotation in the plan view, respectively, of the force P_f;

φ_s – is a coefficient that takes into account the effect of the angle γ_{pl} of the knife's rotation in the plan view, respectively, of the force P_s;

$\varphi_{s.c}$ – is a coefficient that takes into account the effect of the angle γ_{pl} of the knife's rotation in the plan view, respectively, of the force $P_{s.c}$.

Table 2. Theoretical data

α	Soil cutting force P, kN		
	Loam	Marl clay	Argillite
0°	3,86	6,25	9,18
20°	3,96	6,19	9,73
40°	3,96	5,75	10,8
60°	2,59	4,59	4,98
80°	2,19	3,71	4,21

For the laboratory bench, taking into account the similarity coefficients used in physical modelling [11], the parameters and calculation results are given in Table 3. Based on the data in Table 3, we constructed graphs of the cutting force change depending on the angle of the cutting force direction (Fig. 7).

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Table 3. Data

α	Loam	Marl clay	Argillite
0°	0,84	3,37	10,1
20°	0,87	3,34	10,7
40°	0,87	3,1	11,88
60°	0,56	2,47	5,47
80°	0,48	2	5,12

Graphical display of the data obtained after applying the similarity coefficients in Fig. 7

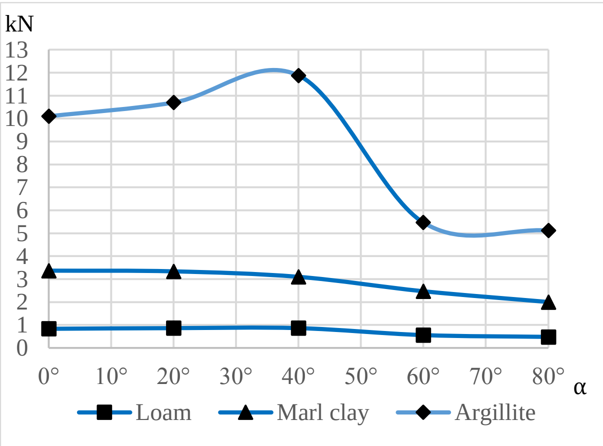

Fig. 7. Graph of cutting forces based on theoretical data

In the course of experimental studies, we simultaneously measured normal and orthogonal cutting forces, which perform the work of destroying and overcoming the soil resistance to cutting. The methods of measuring resistance with resistance sensors are based on the strain gauge effect, i.e., a change in the electrical (i.e., ohmic) resistance of the metal sensor wire during its elastic deformation using strain gauge beams. The signal was amplified by modern instrumental amplifiers manufactured by Analog Devices. A 10-bit module was used as an analogue-to-digital converter (ADC), which is part of the PIC (Peripheral Interface Controller) microcontroller family. Thus, the measurement data were recorded using high-tech measuring and recording equipment, which made it possible to quickly and without repetition obtain sufficiently accurate estimates of the interaction of the spatially oriented knife of the dumping equipment from the primary data. The obtained results in the form of an array of points were recorded in real time (oscillograms) (Fig.8 - 10).

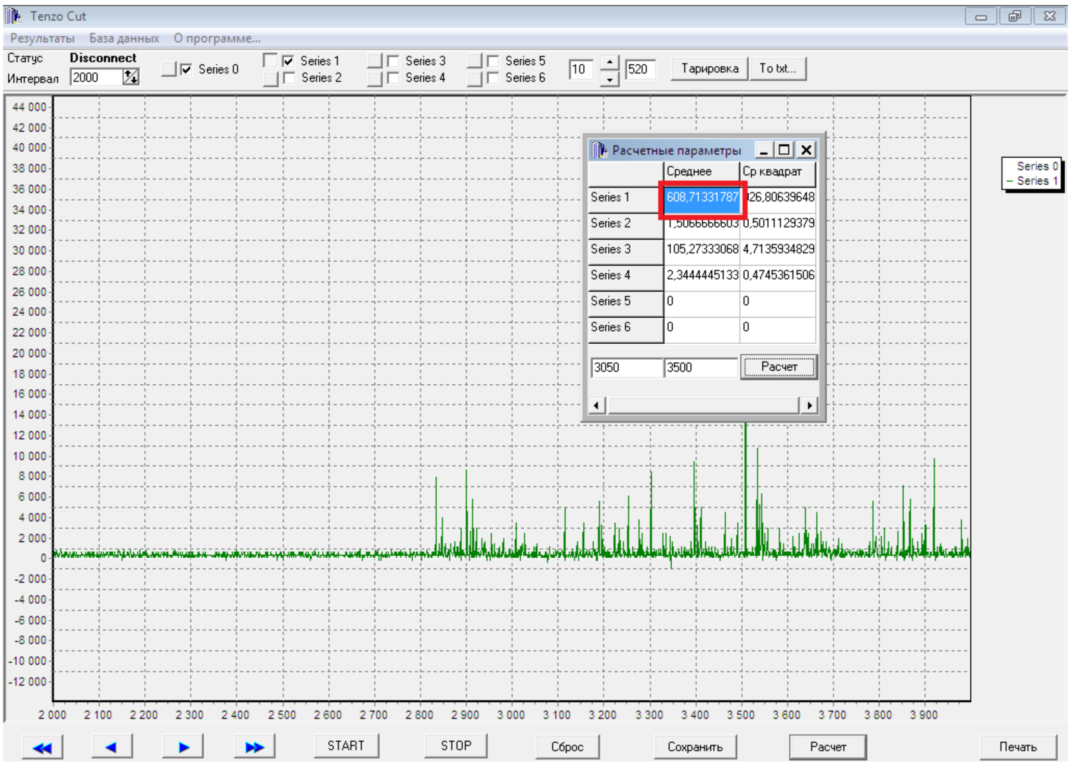

Fig. 8. Cutting force oscillogram of soil category III at cutting force direction angle α = 60°

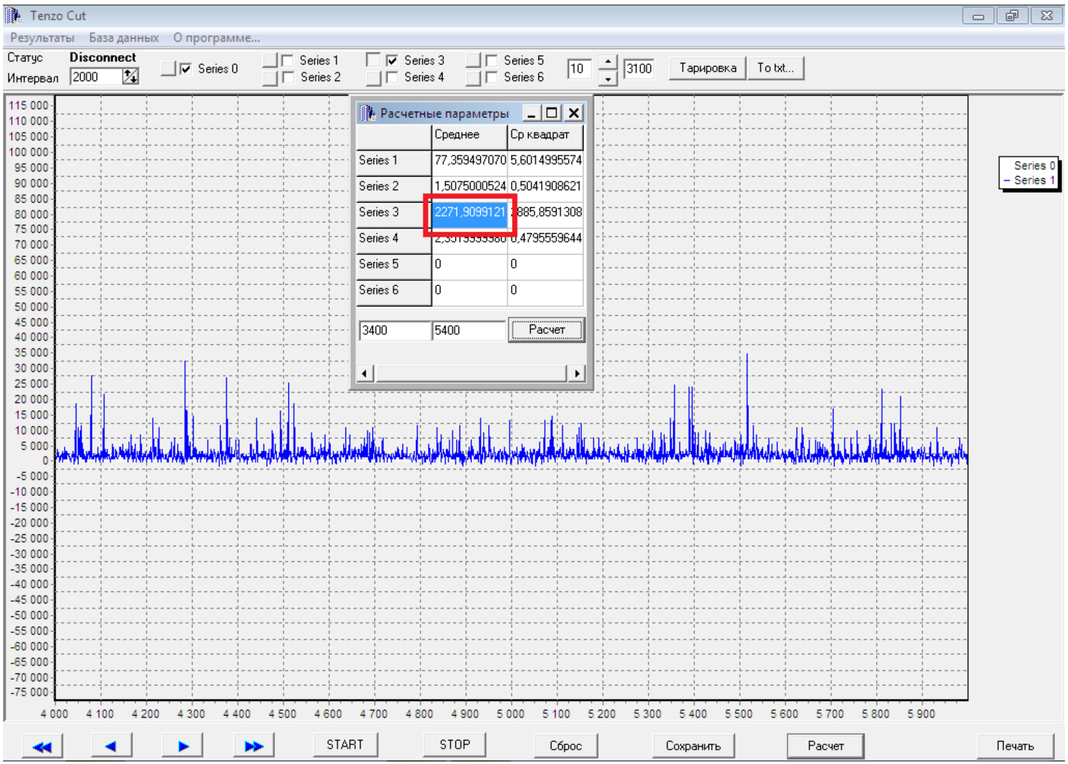

Fig. 9. Cutting force oscillogram of soil category IV at cutting force direction angle α = 60°

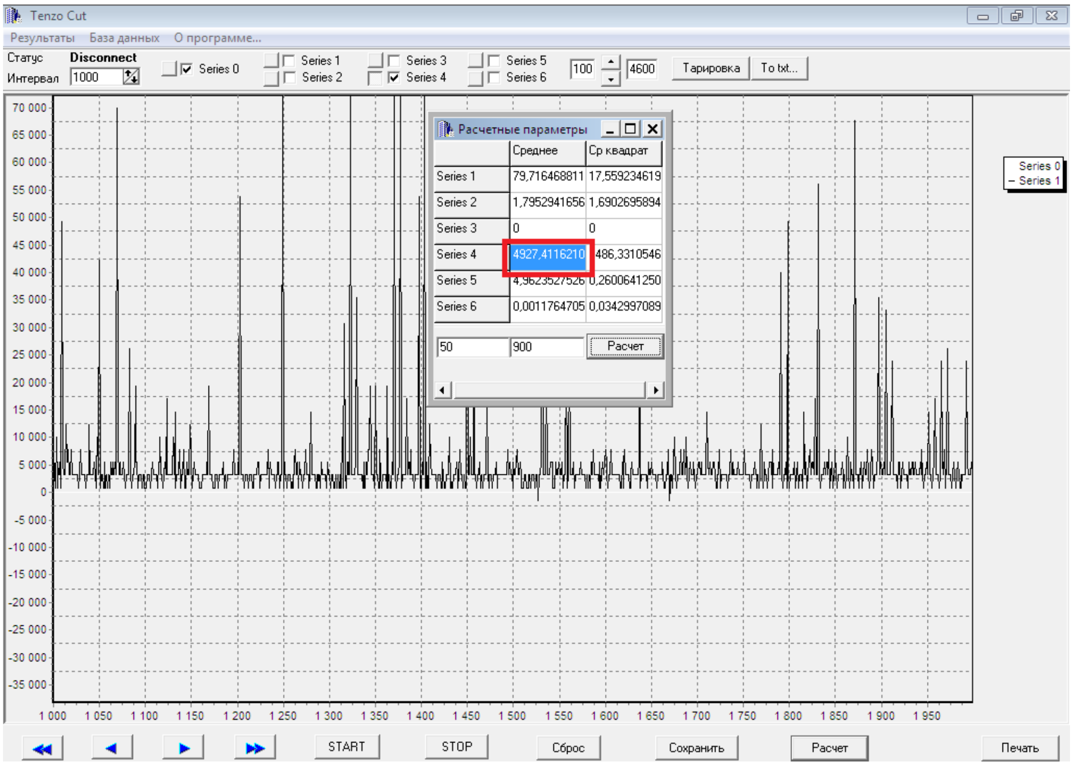

Fig. 10. Cutting force oscillogram of soil category V at cutting force direction angle α = 60°

Subsequently, the oscillograms were processed using modern software called Tenzo Cut, which eliminated the time-consuming data processing process. This minimised the number of measurements of the cutting force at a given accuracy and reliability of the test results with the reliability of the data from 0.90 to 0.95.

The obtained oscillograms were brought to the beginning of the horizontal coordinate axis by shifting the lowest value to the zero mark

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and programmatically converted to power values *N* (taring).

After taring the oscillograms, the average value of the cutting forces was determined using the software calculation module spatially oriented on the dynamometer bench.

Having previously set the range on the tared oscillogram, the starting and ending marks on the horizontal coordinate axis were set. The results of the calculations are shown in Table 4.

Table 4. Experimental data

α	Soil cutting force P, kN		
	Loam	Marl clay	Argillite
0°	0,919	3,091	9,092
20°	0,951	3,072	9,632
40°	0,949	2,853	10,734
60°	0,608	2,271	4,927
80°	0,518	1,841	4,627

Graphical representation of the data obtained after the experimental studies in (Fig. 11).

To verify the adequacy of the results of theoretical calculations, a comparative analysis of similar parameters determined experimentally was carried out. The values of the cutting forces that perform the work of destroying and overcoming the resistance of the soil to cutting, which were determined theoretically, taking into account the similarity coefficients used in physical modelling for the above laboratory stand for recording cutting forces with a spatially oriented knife, are compared with the results of the cutting forces determined experimentally on this stand (Fig. 12).

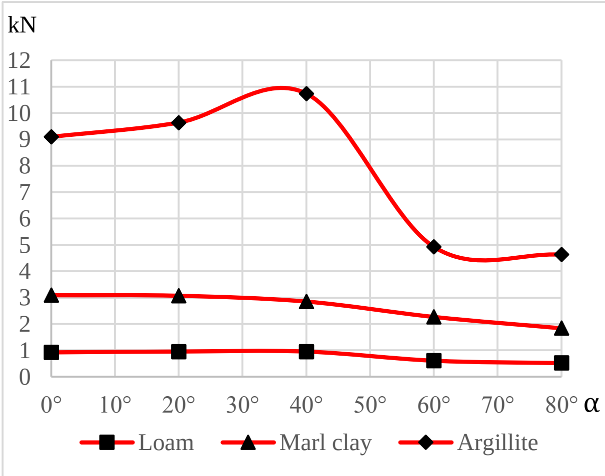

Fig. 11. Graph of cutting forces based on experimental data

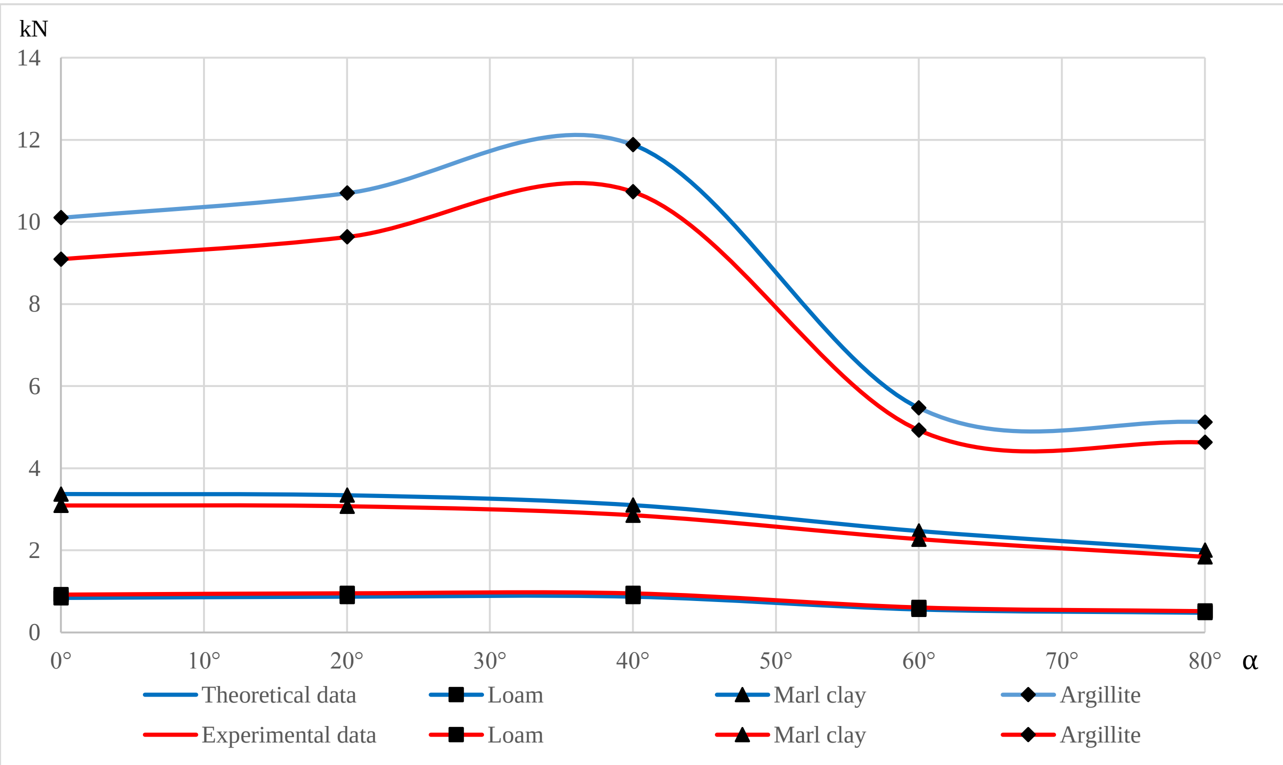

Fig.12. Summary graph of theoretical and experimental cutting forces

The accuracy of determining the cutting force obtained by theoretical and experimental methods is determined by the dependence:

$$\Delta_{\delta} = \frac{|\delta_E - \delta_T|}{\delta_E} \cdot 100\%$$

Where δ_E – is the value from the graph obtained experimentally; δ_T – is the value from the graph obtained theoretically [16].

The maximum value of the error in determining the cutting force by theoretical and experimental methods on the laboratory bench for recording cutting forces by a spatially oriented knife of dump equipment is Δ_{δ}=10,06%.

As a result of the experimental studies, the value of the cutting force of the working environment at different values of the angle of direction of the cutting force *α* by the working tool was determined. Comparison of theoretical and experimental results of determining the cutting force showed their sufficient convergence and, accordingly, the legitimacy of using analytical expressions in calculating the power parameters of machines with spatially oriented knife of dumping equipment.

RESEARCH CONCLUSIONS

As a result of the studies carried out for the dynamometric stand for recording the force load during the study of the cutting process with a spatially oriented knife of the bulldozer blade, the cutting force of soils was analytically determined. According to the results of theoretical studies, it was found that the limits of change in the cutting force determined for a natural machine with spatially oriented knives of the blade equipment and for the laboratory testbed are the same, and the nature of their change is also similar and is related to each other by the similarity coefficient.

In order to verify the adequacy of theoretical calculations on the dynamometer, experimental studies of cutting the working environment were carried out. The experimental studies fully confirm the adequacy of the theoretical calculations, and the comparison of theoretical and experimental results of determining the cutting force showed their sufficient convergence and, accordingly, the legitimacy of using analytical expressions in calculating the power parameters of machines with spatially oriented knives.

The maximum value of the error in determining the cutting force by theoretical and experimental methods on the laboratory bench for recording cutting forces by spatially oriented knives of the blade equipment is Δ_{δ}=10,06%.

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Результати експериментальних досліджень різання ґрунтів просторово орієнтованими ножами відвального обладнання

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Анотація. Для проведення експериментальних досліджень процесу різання робочого середовища просторово орієнтованими ножами відвального обладнання, доопрацьовано динамометричний стенд реєстрації силового навантаження авторської конструкції КНУБА, що дозволило провести повноцінні експериментальні дослідження з врахуванням всіх чинних факторів взаємодії робочого середовища та робочого органу під час різання. В якості робочого середовища запропоновано використання ґрунтів ІІІ, IV, та V категорії. В результаті проведених досліджень для динамометричного стенда реєстрації силового навантаження при дослідженні процесу різання просторово орієнтованим ножем аналітично визначено сили різання при різних кутах α її відхилення, які виконують роботу по руйнуванню і подоланню опору ґрунту різанню. За результатами теоретичних досліджень встановлено, що межі сили різання, визначеної для натуральної установки з просторово орієнтованими ножами та для лабораторного стенду, однакові, а характер їх зміни також подібний і пов'язаний між собою коефіцієнтом подібності. З метою перевірки адекватності теоретичних розрахунків на динамометричному стенді проведено експериментальні дослідження різання робочого середовища. При проведенні експериментальних досліджень одночасно проводилось вимірювання нормальних та ортогональних зусиль, які виконують роботу з руйнування і подолання опору ґрунту різанню. Проведені експериментальні дослідження в повній мірі підтверджують адекватність теоретичних розрахунків, а порівняння теоретичних та експериментальних результатів визначення сили різання показало їх достатню збіжність і, відповідно, правомірність використання аналітичних виразів при розрахунку силових параметрів машин з просторово орієнтованими ножами відвального обладнання. Величини сили різання, що виконують роботу по руйнуванню і подоланню опору ґрунту різанню, що визначались теоретичним шляхом із врахуванням коефіцієнтів подібності, використаних при фізичному моделюванні для наведеного лабораторного стенда реєстрації сил різання просторово орієнтованими ножами відвального обладнання, порівняно з результатами сили різання, визначених експериментальним шляхом на даному стенді. Максимальне значення похибки визначення сили різання теоретичним та експериментальним шляхом на лабораторному стенді реєстрації сил різання просторово орієнтованими ножами відвального обладнання становить Δ_{δ}=10,06%.

Ключові слова: косокутне різання, просторово-орієнтований, відвал екскаватора, лабораторний стенд, експериментальні дослідження.