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OPTIMIZATION OF SOIL CUTTING PROCESS BY RIPPER TIP WITH DYNAMIC CUTTING EDGE

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The interaction between the ripper tip with the dynamic cutting edge on the pneumatic accumulator and the soil massif is studied. The rheological models of the soil and the patterns of its deformation under the action of the working element are analyzed. The tip movement speed, the change in cutting force and the formation of the compressed zone for different soil categories are determined by analytical and experimental methods. It's established that the tip use with the dynamic cutting edge reduces peak and average loads, reduces friction and vibrations, which increases energy efficiency and extends the resource of the working element. The greatest effect is achieved when developing light and medium-density soils, and load stabilization is preserved for strong soils.

Keywords: dynamic cutting edge, pneumatic accumulator, earthworks, rheological model, energy efficiency, cutting force, soil, ripper tip, process intensification.

Introduction. Modern transport construction, mining and agriculture are characterized by significant volumes of earthworks that must be carried out throughout the year, including in winter. In conditions of increased energy consumption and intensive wear of working tools, the use of highly efficient machines and technologies is of particular relevance. This leads to a constant search for solutions aimed at increasing labor productivity, reducing fuel consumption and increasing the resource of working elements [1–3].

A wide range of machines are used to perform earthworks in various industries:

- in construction – bulldozers, graders and excavators for cutting, moving and planning soils; milling drums of road machines for removing old asphalt pavement or preparing the base for laying new road pavement;
- in agriculture – plows and deep cultivators for basic tillage; cultivators and disc harrows for crushing clods and destroying the compacted layer of the arable horizon;
- in the mining industry – equipment for excavation of soft rocks, clay and sand deposits; road headers and rotary excavators for work in heterogeneous and difficult soil conditions;
- in specialized machines – drilling rigs for the arrangement of soil piles and wells; trench excavators for laying underground communications; road soil stabilizers for mixing the soil base with binders (cement, lime) in order to increase its strength.

At the same time, the experience of operation shows that the use of machines with traditional working elements does not always provide the necessary pace of work performance and the achievement for modern productivity indicators [4]. This encourages the improvement of existing structures, the development of new types of working elements and the introduction of comprehensive technological solutions aimed at intensifying the processes of developing, moving and compacting soils.

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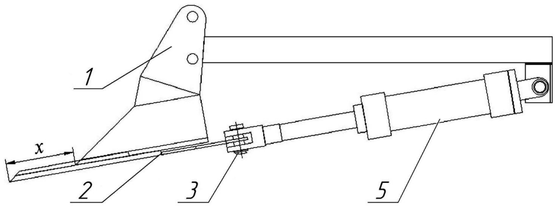
Analysis of publications. The proposed solution to the problem is based on establishing the regularities of the process of destruction of the soil massif by the ripper tip with the dynamic cutting edge with the pneumatic accumulator (DCEP). This design ensures the accumulation of potential energy during soil crushing, with its subsequent transformation into kinetic energy and directed to the soil massif at the optimal moment of time.

The developed ripper tip is fundamentally different from the well-known analogues, which makes it possible to achieve a new technical effect – increasing the productivity of the soil development process while reducing the specific energy costs for the technological operation. Thus, the design improvement is based on the task of increasing the efficiency of using the working machine by optimizing energy processes.

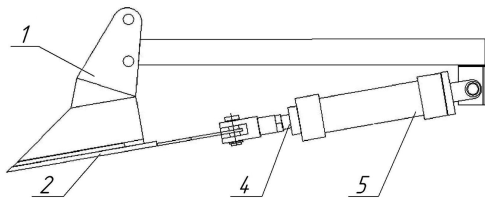
The process of energy accumulation and transformation is realized due to the special structure of the tip (Fig. 1). The design includes a rack with a tip 1, which has the movable (dynamic) cutting edge 2, articulated by the pin 3 with the rod 4 of the pneumatic accumulator 5. During operation, the rod moves the cutting edge by the value x, which ensures the accumulation of energy and its metered transfer to the soil massif [5].

The proposed technical solution allows you to reduce the maximum values of cutting resistance due to the preliminary energy pulse, increase the uniformity of the load on the working unit, which has a positive effect on its durability, as well as ensure the stability of the cutting depth in heterogeneous soil conditions.

Purpose of the paper. The purpose of the study is to establish and reveal the mechanical processes occurring in the stressed-deformed contact zone of the working medium with the ripper working element, equipped by tip with the dynamic cutting edge and the pneumatic accumulator.



(a)



(b)

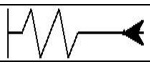
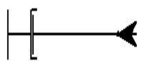
Fig. 1. Ripper tip with dynamic cutting edge on the pneumatic accumulator:
(a) – working position with cutting edge; (b) – sharp knife

Research results. To achieve this goal, it is envisaged to create a visual representation of the nature of changes in stresses and deformations of the medium depending on its physical and mechanical properties during the mechanical impact of the working element. This approach is implemented by applying rheological models that make it possible to describe the main patterns of interaction of the working element with the soil massif.

The medium is considered in the form of simplified mechanical systems, which consist of individual elements or their combinations (Table 1), which simulate the basic physical and mechanical properties of the soil and reproduce the nature of the stress-strain state under the influence of external loads [6]. This approach allows you to conduct an analytical and experimental analysis of the behavior of the soil massif and substantiate the parameters of the design of the dynamic cutting edge.

Table 1

Main types of rheological models

Model name	Scheme	Basic equation	Nature of deformation
Hooke's model		$\sigma = E\varepsilon$	Elastic, fully reversible deformation, proportional to stress
Newton's model		$\tau = \eta \dfrac{dv}{dz}$	Viscous, irreversible deformation, proportional to the rate of load application

The rheological model of an elastic material (Hooke's model) is presented in the form of the spring, which characterizes the property of elasticity and describes the proportional relationship between stress and strain (Table 1). The graph of the stress dependence on strain at loading and subsequent unloading is linear in nature and is determined by the well-known Hooke's law:

$$\sigma = E\varepsilon ,$$

where E – elasticity modulus (Young's modulus); ε – relative deformation.

The model of the perfectly viscous element (Newton's model) is considered as a system consisting of the piston that moves inside the cylinder filled with liquid, with thin calibrated holes. At the same time, the work of external forces is spent on overcoming the forces of internal friction of the liquid and completely passes into heat, which makes the process irreversible. Such a model reproduces the behavior of environments where deformation is of the high-speed nature and depends on the load action time.

In this model, the stress is proportional to the strain rate gradient (load application rate):

$$\tau = \eta \frac{dv}{dz} ,$$

where η – dynamic viscosity factor; v – movement speed; z – distance.

The parallel combination of these models (the so-called Maxwell–Voigt model or other combined viscoelastic schemes) makes it possible to describe the properties of real media, in particular air in the pneumatic accumulator and the soil massif in a state of stress-strain interaction [7–9]. This approach allows taking into account both the elastic and viscous components of the deformation process, which is important for optimizing the parameters of the dynamic cutting edge. A rheological model of the interaction between the ripper tip with DRCP and the soil massif has been compiled with the assumption that the metal elements are not deformed (Fig. 2).

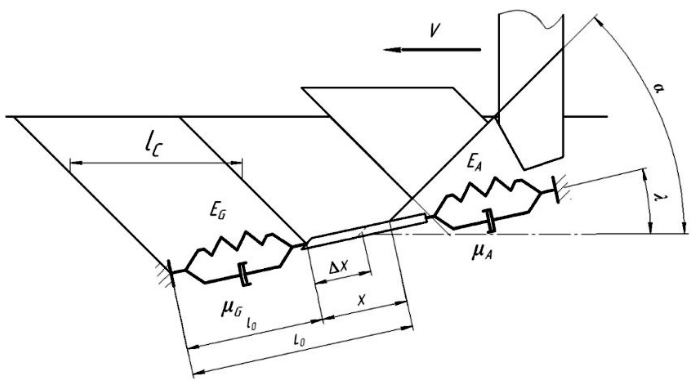


Fig. 2. Rheological model of interaction between the ripper tip with dynamic cutting edge on the pneumatic accumulator and the soil massif

The following rheological equations correspond to the models of deformity of elementary volumes between the ripper tip with DCEP and the soil massif, respectively

$$F_A = \int_0^s E_A \left(\xi_A + \frac{\mu_A}{E_A} \dot{\xi}_A \right) ds ; \tag{1}$$

$$F_G = \int_0^s E_G \left(\xi_G + \frac{\mu_G}{E_G} \dot{\xi}_G \right) ds , \tag{2}$$

where E_A, E_G – respectively the modulus of deformation of air and soil; μ_A, μ_G – respectively the factor of internal friction for air and soil; ξ_A, ξ_G, $\dot{\xi}_A$, $\dot{\xi}_G$ – relative deformations and deformation velocities of air (the ripper tip movement with DCEP) and soil, respectively [10].

The changes that occur with rheological models during soil cutting are determined based on the scheme.

If the time t is counted from the moment when $x = x_1$, then for any t within the contact

$$\Delta x + \Delta l = \Delta L ; \tag{3}$$

$$\frac{\Delta x}{dt} + \frac{\Delta l}{dt} = \frac{\Delta L}{dt} , \tag{4}$$

where Δx – relocation of the ripper tip with DCEP, Δl – soil deformation.

$$\xi_A \cdot E_A + \dot{\xi}_A \mu_A = \xi_G E_G + \dot{\xi}_G \mu_G ; \quad (5)$$

$$K_x = \frac{dl/dt}{dx/dt} = \frac{dl}{dx} \approx \frac{\Delta l}{\Delta x} . \quad (6)$$

Taking into account the depth factor medical history

$$K_x = \frac{k_g \left(E_G \Delta L + \mu_G \dot{L} T_c \right)}{P_z \left(E_A \Delta L + \mu_A \dot{L} \right)} , \quad (7)$$

where P_z – pressure in the pneumatic cylinder, $T_c = 1/\bar{n}_M$ – period of soil chipping, the value is the inverse of the average frequency for oscillations of the soil cutting force maximums $\bar{n}_M$

$$\bar{n}_M = \frac{\bar{n}_0}{0,63...0,87} ,$$

where $\bar{n}_0 = (2,0...2,8)V/H$ – average frequency of fluctuations in the soil cutting force; H – depth of loosening; V – the rate of tip introduction.

When calculating the rate of soil deformation in accordance with the theorem on the average integral value, the average value ΔL and $\dot{L}$.

$$\Delta L = l_0 + x_0 , \quad (8)$$

since it is accepted that $\alpha = 45°$, $\lambda \Rightarrow 0$ then $\cos\lambda \Rightarrow 1$, then $l_0 \approx l_c$.

Knowing the tabular values of E_A , E_G , μ_A , μ_G and specifying the geometric parameters, K_x is determined, then the displacement of the ripper tip with DCEP is determined Δx

$$\Delta x = \frac{\Delta L}{\left| (1 - K_x) \right|} . \quad (9)$$

On the basis of the (9) equation solution, the dependence graphs of the ripper tip movement with DCEP on the geometric and physical-mechanical parameters of the loam cutting process are constructed (Fig. 3, Fig. 4). The analysis of the obtained dependencies allows you to determine the optimal parameters of the design and operating modes of the ripper tip, which provide an increase in the efficiency of destruction of the soil massif with minimal energy consumption.

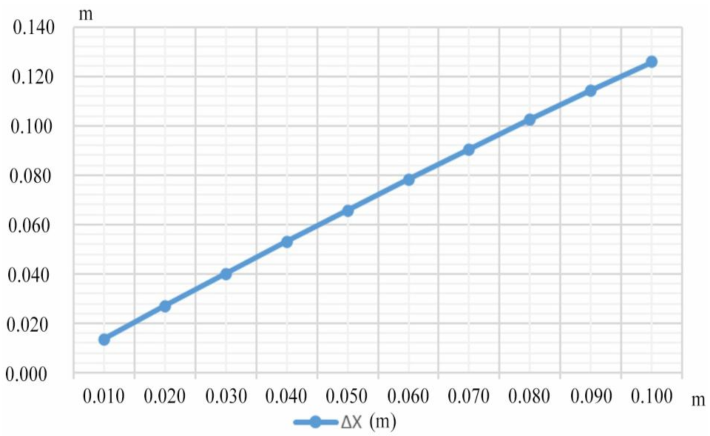


Fig. 3. Dependence graphs of the ripper tip movement with DCEP on tip width at 10 MPa pressure in the pneumatic accumulator

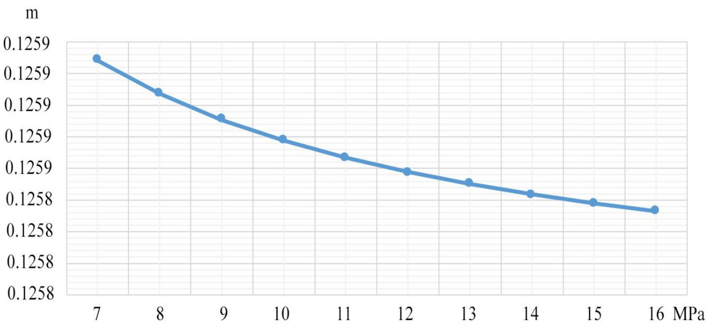


Fig. 4. Dependence graphs of the ripper tip displacement with DCEP on pressure in the pneumatic accumulator at 0.1 m tip width

Therefore, as a result of the ripper tip movement with DCEP, potential energy is accumulated by compressing air in the pneumatic accumulator

$$U_P = \frac{1}{2} P_B \Delta x , \quad (10)$$

where P_B – force for erecting the cutting edge.

At the moment of chipping

the soil, the force P_B is directed to zero, as a result of which the ripper tip with DCEP tries to take its initial position when $x = x_0$, and the potential energy U_P is converted into the kinetic energy U_K of the ripper tip motion with DCEP

$$U_P = U_K = \frac{M_{pic} \cdot V_{pic}{}^2}{2}, \tag{11}$$

where V_{pic} – speed of the ripper tip with DCEP.

Knowing the mass of the ripper tip with DCEP M_{pic}:

$$M_{pic} = L_{pic} \cdot b_{pic} \cdot c_{pic} \cdot \rho_{pic}, \tag{12}$$

where pic – density of the material ripper tip with DCEP (steel), from the expression (11) the ripper tip speed is determined (Fig. 5, Fig. 6)

$$V_{pic} = \sqrt{2U_P / M_{pic}}. \tag{13}$$

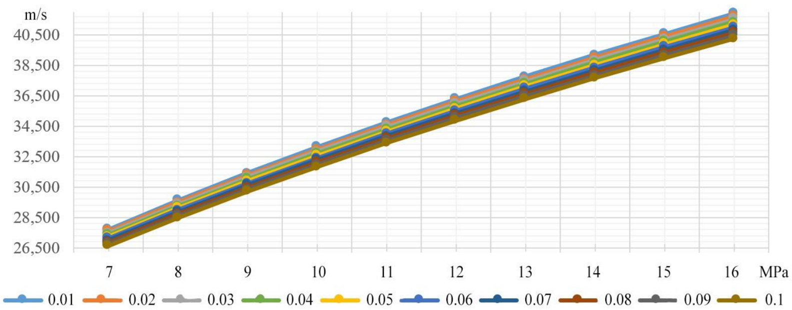


Fig. 5. Dependence graphs of the ripper tip movement speed with DCEP on pressure in the pneumatic accumulator at from 0.01 to 0.1 m tip width with 0.01 m step

Calculations of the ripper tip movement speed with DCEP in soils of seven strength categories, with similar tips with a width of $b_K = 0{,}01$ m to $b_K = 0{,}1$ m, with a step of 0.01 m, changing the pressure in the pneumatic cylinder P_z from 6 to 15 MPa, with a step of 1 MPa, were carried out (Fig. 7).

It has been established that the ripper tip speed with DCEP numerically depends on the soil category and rapidly decreases with an increase in the width of the tip. It acquires a value of more than 9 m/s (which indicates the presence of signs of a dynamic process of soil destruction) [11, 12].

Since the ripper tip with DCEP provides the application of a load at a speed exceeding 9 m/s, it is advisable to consider its action from the standpoint of the theory of strain wave propagation. This approach allows you to more accurately describe the nature of the interaction of the working

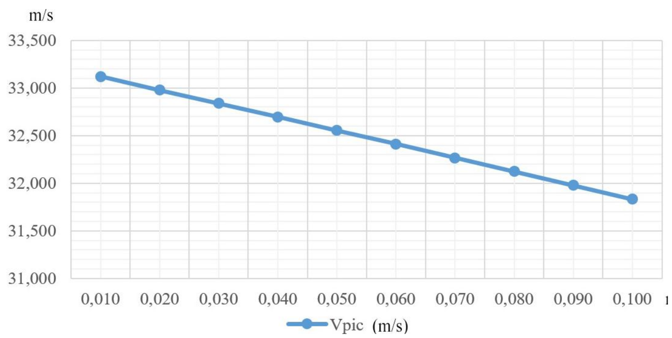


Fig. 6. Dependence graphs of the ripper tip movement speed with DCEP on tip width at 10 MPa pressure in the pneumatic accumulator

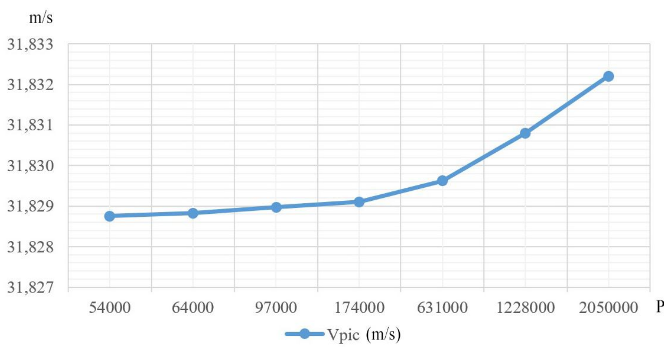


Fig. 7. Dependence of the ripper tip speed with DCEP on soil strength categories at 10 MPa pressure in the pneumatic accumulator

element with the soil massif, taking into account the inertial effects and the dynamic component of the destruction process.

The notations used in the following formula are given in accordance with [13, 14], which ensures the correctness of the reproduction of the mathematical model and the ability to compare the results obtained with known theoretical solutions

$$P = \frac{Uk_D S}{2vk_\alpha}, \tag{14}$$

Equating the frontal surface area of the ripper tip to the contact area

$$S = S_{pic} = c \cdot b \text{, and } v = V_{pic},$$

where c – thickness of the ripper tip on which the cutting edge is located; b – width of the ripper tip on which the cutting edge is located (tip width) from the expression (14), the dynamic cutting force with the cutting edge is obtained

$$P_D = \frac{uk_D S_{pic}}{2V_{pic}k_\alpha}, \tag{15}$$

where $u = \sqrt{\dfrac{E_G(1-\mu)}{I_G(1+\mu)(1-2\mu)}}$ – strain wave speed; $k_D = I_G V_{pic}{}^2 + \sigma_G \varepsilon_G$ – specific dynamic resistance of the soil; k_α – factor that takes into account the sharpening angle of the working element; μ – angle of friction for the soil against the knife; I_G – mass density of the soil; σ_G – tensile strength of the soil under static compression; ε_G – dynamic deformation of the soil.

Thus, P_B ripper tip with DCEP is moved under the force action, compressing the air in the pneumatic accumulator, and when returning to its original position, it sharply acts on the soil element (hits) with a P_D force.

The energy of a single impact of the ripper tip with DCEP on the soil was determined

$$E_{pic} = \frac{M_{pic} \cdot V_{pic}^2}{2}. \tag{16}$$

Knowing the energy of a single impact, the penetration depth of the ripper tip with DCEP into the soil in one blow δ_{pic} and the duration of the t_{ship} shock pulse were determined

$$\delta_{pic} = \frac{2 \cdot E_{pic} \cdot V_{pic} \cdot k_\alpha}{u \cdot k_D \cdot S_{pic}}; \tag{17}$$

$$t_{ship} = \frac{2 \cdot E_{pic} \cdot k_\alpha}{S_{pic} \cdot (u - V_{pic}) \cdot k_D}. \tag{18}$$

From here, the length of the compressed soil zone due to the load in the ripper tip zone is determined (Fig. 8, Fig. 9)

$$l_{pic} = \left(u - V_{pic}\right) \cdot t_{ship}. \tag{19}$$

The compressed zone of the soil, formed as a result

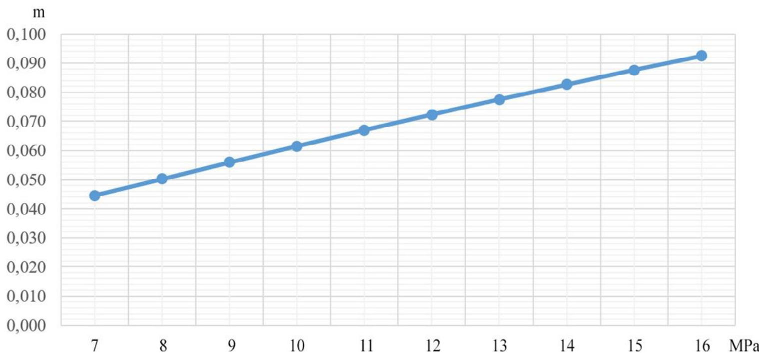


Fig. 8. Dependence graphs of the compressed soil zone length on pressure in the pneumatic accumulator at 0.1 m tip width

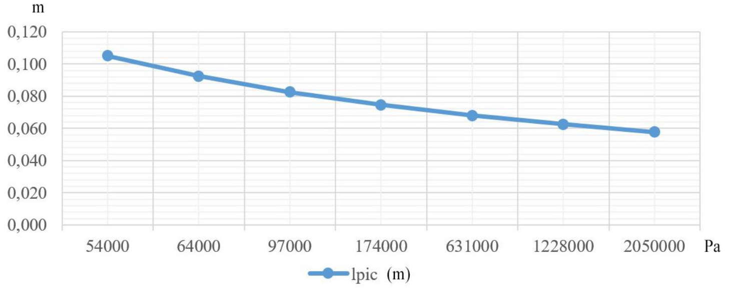


Fig. 9. Dependence of the compressed soil zone length on the soil strength categories at 10 MPa pressure in the pneumatic accumulator

of the dynamic action of the ripper tip with DCEP, is not limited by the direction of propagation of the deformation wave. According to Coulomb's law, under which the complex stress state of the soil is also subject, in addition to the main normal stress σ in the soil, there is also the main lateral stress $\bar{\sigma}$, which acts in the direction perpendicular to the direction of wave propagation and forms a compressed zone of the soil. Lateral pressure $k_\sigma = \frac{\bar{\sigma}}{\sigma}$ factor for clay soils it is in the range of 0.11–0.82, for hard soils 0.25–0.37 [6, 15].

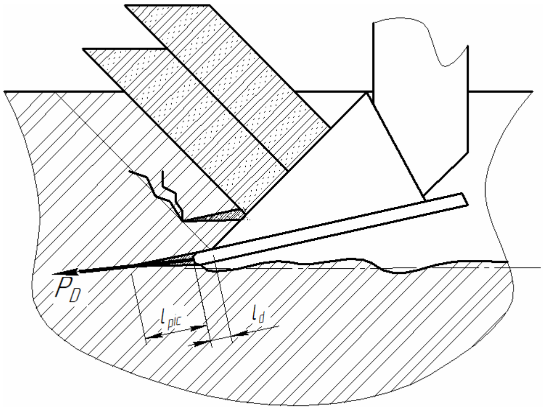


Fig. 10. Stress distribution scheme in the soil under the action of the ripper tip with dynamic cutting edge

Thus, it is advisable to consider the force of cutting the soil with the ripper tip with the dynamic cutting edge with the pneumatic accumulator according to the principle of superpositions of influence [5]

$$P_S = P_W - \left(P_D - P_B \sin\lambda\right)\frac{1}{l_c} l_{pic} \sin\lambda \,. \tag{20}$$

Substituting the elements of the components into the expression (20), we get a mathematical model for determining the force of cutting the soil with the ripper tip made of DCEP

$$P_S = m_f H b_k + 2m_{si}H^2 + 2m_{si.c}H - \left(\frac{uk_D S_{pic}}{2V_{pic}k_\alpha} - E_A \Delta x D_c \sin\lambda\right)\frac{1}{l_c} l_{pic} \sin\lambda \,. \tag{21}$$

The calculation of soil cutting of these soil categories is carried out according to the classical formula of static cutting by Yuri Vetrov and according to the expression (20), the results are presented in (Fig. 11).

Note. P_W (N) is the force of cutting soil with an ordinary tip. P_S (N) is the force of cutting soil by ripper tip with the dynamic cutting edge on the pneumatic accumulator.

The analysis of the experimental and calculated data obtained made it possible to identify several characteristic zones of change in cutting force when using the tip with the dynamic cutting edge on the pneumatic accumulator:

1. Initial section (≈ 50–70 kPa): in both cases, there is an increase in cutting force; a local maximum is detected ≈ 8–9·10^6 N for P_W and ≈ 7·10^6 N for P_S; already at this stage, it is noticeable that the use of the dynamic cutting edge reduces peak loads.
2. Middle zone (≈ 70–170 kPa): both curves show a decrease in cutting force to minimum values (≈ 4–5·10^6 N); the values are slightly higher for P_W than indicating lower cutting resistance when using the pneumatic accumulator for P_S.
3. Transition zone (≈ 174 kPa): there is a sharp increase in cutting force; the climb is more rapid for P_W, while P_S provides a smoother growth pattern; this indicates the ability of the pneumatic accumulator to smooth out the dynamic load surge, reducing vibration effects on the working element.
4. High pressure zone (≈ 600–1200 kPa): the curves reach a conditional plateau $P_W \approx 66\cdot10^6$ N, $P_S \approx 63\cdot10^6$ N; the difference is ≈ 3·10^6 N, which corresponds to the saving of cutting force of about 5%.

Thus, the use of the ripper tip with DCEP ensures a reduction in peak loads on the tool; reduction of average cutting force by 3–10% depending on pressure; increasing the energy efficiency of the process, as well as reducing the wear of the working element by mitigating dynamic shocks and vibrations.

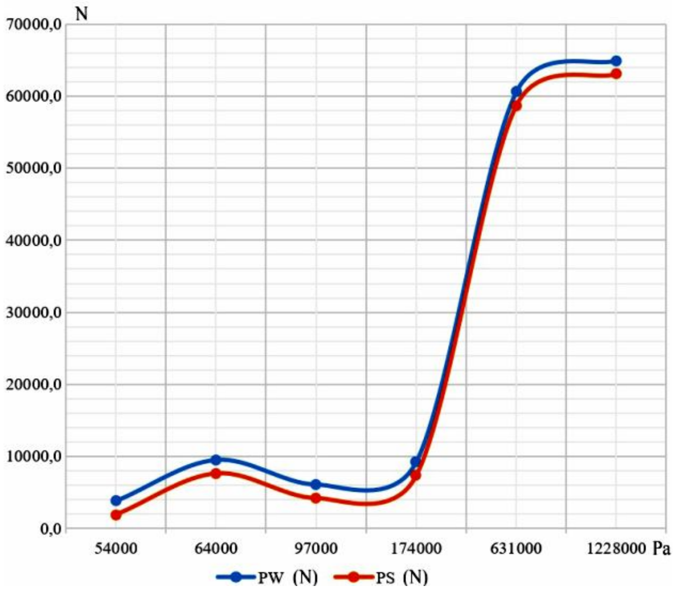


Fig. 11. Comparison of the force to overcome soil resistance to cutting by conventional sharp tip and ripper tip with DCEP when cutting soils of different strength in the range from 54 to 1288 kPa

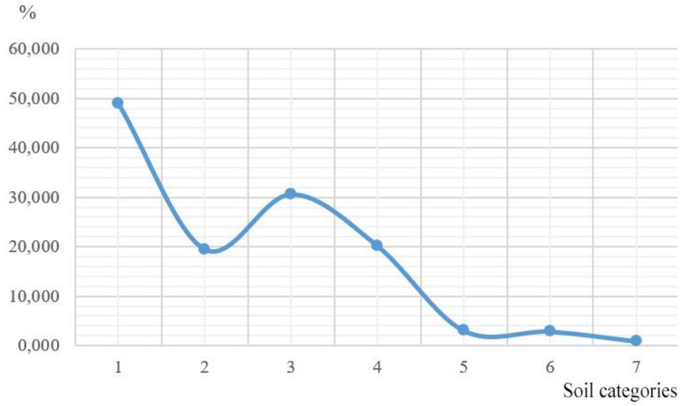


Fig. 12. Percentage value of force reduction to overcome soil resistance to cutting by tip with DCEP when cutting soils of different strength in the range from 54 to 1288 kPa

Additionally, the dependence of the relative decrease in the cutting force on the soil category is calculated (Fig. 12). The analysis shows that the maximum effect is observed during the development of light soils (category 1), where the reduction in cutting force reaches ≈ 50%. For soils of medium density (categories 2–3), the effect is 20–30%, while for heavy soils (categories 5–7) it decreases to 2–5%. This indicates that the use of the ripper tip with DCEP is most appropriate in light and medium density soils, where significant energy savings in the cutting process and an increase in the resource are provided.

Conclusions. The cutter use with the dynamic cutting edge on the pneumatic accumulator allows:

– reduce peak loads, as the pneumatic accumulator smooths out fluctuations in cutting force and mitigates dynamic shocks, reducing maximum energy costs;

– improve chip formation and uniformity of soil grinding, which reduces friction between the tool and the soil and reduces heat loss;

– improve energy efficiency by accumulating some of the oscillating energy and directing it to useful cutting operation;

– reduce the overall energy intensity of the process by reducing the average cutting force, friction and vibration losses, which ensures energy savings, process stability, increased tool life and improved tillage quality.

Thus, the ripper tip with the dynamic cutting edge on the pneumatic accumulator makes the soil development process more productive, energy-efficient and reliable, especially in conditions of heavy or heterogeneous soils.

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ОПТИМІЗАЦІЯ ПРОЦЕСУ РІЗАННЯ ҐРУНТУ НАКОНЕЧНИКОМ РОЗПУШУВАЧА З ДИНАМІЧНОЮ РІЖУЧОЮ КРОМКОЮ

У роботі проведено дослідження механічних процесів взаємодії наконечника розпушувача з динамічною ріжучою кромкою на пневмоакумуляторі з ґрунтовим масивом. Розглянуто реологічні моделі ґрунту, що описують його пружні та в'язкопружні властивості, а також закономірності деформації під дією робочого органу. На основі поєднання аналітичних методів і експериментальних випробувань досліджено швидкість переміщення наконечника розпушувача, динаміку зміни сили різання та характер формування стисненої зони для різних категорій ґрунту. Отримані результати дозволили встановити закономірності впливу параметрів наконечника розпушувача на силові навантаження, енергетичні витрати та стабільність технологічного процесу. Показано, що використання наконечника з динамічною ріжучою кромкою на пневмоакумуляторі сприяє зниженню пікових і середніх навантажень, зменшенню сил тертя й вібраційних коливань, що веде до підвищення енергоефективності, зменшення динамічних ударів і збільшення ресурсу робочого органу. Встановлено, що максимальний ефект досягається під час розробки легких і середньої щільності ґрунтів, де спостерігається найбільше зниження сили різання та найвища стабільність процесу. Для міцних ґрунтів енергетичний ефект менш виражений, однак позитивний вплив на стабілізацію навантажень зберігається. Практичне значення отриманих результатів полягає у можливості вдосконалення конструкцій наконечників розпушувачів, обґрунтуванні раціональних режимів їхньої роботи, а також підвищенні ефективності технологічних процесів під час виконання підготовчих робіт у транспортному та промисловому будівництві, гірничодобувній промисловості та аграрному секторі.

Ключові слова: динамічна ріжуча кромка, пневмоакумулятор, земляні роботи, реологічна модель, енергоефективність, сила різання, ґрунт, наконечник розпушувача, інтенсифікація процесу.

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OPTIMIZATION OF SOIL CUTTING PROCESS BY RIPPER TIP WITH DYNAMIC CUTTING EDGE

The mechanical processes of interaction between the ripper tip with the dynamic cutting edge on the pneumatic accumulator and the soil massif are investigated in the paper. Rheological models of the soil are considered, describing its elastic and viscoelastic properties, as well as the regularities of deformation under the action of the working element. The movement speed of the ripper tip, the dynamics of changes in cutting force, and the formation nature of the compressed zone for different soil categories are investigated based on the combination of analytical methods and experimental tests. The results obtained allowed us to establish the influence regularities of the ripper tip parameters on power loads, energy consumption and stability of the technological process. It is shown that the ripper tip use with the dynamic cutting edge on the pneumatic accumulator contributes to the decrease in peak and average loads, the decrease in friction forces and vibration oscillations. This leads to an increase in energy efficiency, the decrease in dynamic shocks and the increase in the resource of the working element. It's found that the maximum effect is achieved during the development of light and medium-density soils, where the greatest reduction in cutting force and the highest process stability are observed. The energy effect is less pronounced for strong soils, but the positive effect on load stabilization is preserved. The practical significance of the results obtained lies in the possibility of improving the designs of ripper tips, substantiating rational modes of their operation. It also aims at increasing the efficiency of technological processes during preparatory works in transport and industrial construction, mining and the agricultural sector.

Keywords: dynamic cutting edge, pneumatic accumulator, earthworks, rheological model, energy efficiency, cutting force, soil, ripper tip, process intensification.

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Пристайло М.О., Балака М.М., Поліщук А.Г., Козак А.А., Гонта І.П. **Оптимізація процесу різання ґрунту наконечником розпушувача з динамічною ріжучою кромкою** // Опір матеріалів і теорія споруд: наук.-техн. збірник. – К.: КНУБА, 2025. – Вип. 115. – С. 325-334.
Досліджено роботу наконечника розпушувача з динамічною ріжучою кромкою на пневмоакумуляторі. Показано зниження пікових навантажень, сили різання та вібрацій, що підвищує енергоефективність і ресурс робочого органу. Найбільший ефект при цьому спостерігається на легких і середньої щільності ґрунтах.
Табл. 1. Іл. 12. Бібліогр. 15.

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Prystailo M.O., Balaka M.M., Polishchuk A.G., Kozak A.A., Honta I.P. **Optimization of soil cutting process by ripper tip with dynamic cutting edge** // Strength of Materials and Theory of Structure: Scientific and technical collected articles. – K.: KNUCA, 2025. – Issue 115. – P. 325-334.
The ripper tip operation with the dynamic cutting edge on the pneumatic accumulator are investigated. The reduction in peak loads, cutting force and vibrations are shown, which increases energy efficiency and the resource of the working element. The greatest effect is observed on light and medium-density soils.
Table 1. Fig. 12. Ref. 15.

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