ритм как один из потенциальных вариантов получения значений характеристик ротора, с последующим обоснованным выбором набора характеристик по методу наименьших квадратов и переходом к задаче балансировки.

Научная новизна. Выявлена основная причина или источник формирования погрешности определения геометрических, массовых и фрикционных характеристик роторных систем на выбеге — разница в погрешностях измерения отдельных параметров выбега: времени и скорости вращения угла поворота ротора. Теоретически при любых, но одинаковых по величине, погрешностях измерения на выбеге (например, его времени) каждого опыта получаем точное значение искомой характеристики.

Практическая значимость. Заключается в возможном использовании штатных остановок роторных систем для мониторинга основных суммарных характеристик роторов — износа рабочих органов, опорных подшипников, изменения величины технологического момента, перераспределения погонной массы ротора, проведения последующей задачи моментной балансировки по методу амплитуд. Предлагаемый вариант решения с использованием метода наименьших квадратов позволит, по своим критериям, обосновано выбрать наиболее подходящий набор характеристик из комплекта решений для нулевого (два возможных решения), не нулевого (обобщенный случай) и положительного дискриминанта момента сопротивления вращения ротора.

Ключевые слова: *роторная система, штатные остановки, выбег, осевой момент инерции, опорные подшипники, фрикционные характеристики, вес ротора, расположение центра масс*

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DESIGN OF TIERED OPERATING UNIT FOR DEEP DIFFERENTIATED TILLAGE

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КОНСТРУКЦІЯ ЯРУСНОГО РОБОЧОГО ОРГАНА ДЛЯ ГЛИБОКОЇ ДИФЕРЕНЦІЙОВАНОЇ РОЗРОБКИ ҐРУНТУ

Purpose. Determining the parameters of tillage operating unit design to provide energy-efficient tillage by means of operating units of excavation machinery.

Methodology. The theoretical studies were based on the general provisions of agricultural mechanics, the elements of continuum theory, Coulomb-Mohr theory of strength. Analytical and graphical analysis of mathematical models was implemented by means of their visual reproduction in space and time on a PC using applied and developed software.

Findings. The basic principles of adapted passive operating unit creation for vertically differentiated deep tillage and recultivation after opencast mining (e.g., the case of amber extraction) are described.

Originality. The mathematical models for the construction of energy-efficient, environmentally focused tools for loosening the soil and differentiated tillage based on the regularity research of the tool for loosening the soil chunk by means of two plane buckle have been obtained.

Practical value. Methods for the design and engineering calculation of tiered operating units for differentiated deep soil tillage have been developed.

Keywords: *operating unit, soil, loosening, tier*

Introduction. Today in Ukraine and abroad, much work accompanied by the tillage of soil, especially in construction, open-cast mining, agriculture and land reclamation has been performed. It makes wide use of machines and mechanisms with passive and active operating units. Therefore, the current issue is to create energy-efficient operating units for excavation machinery [1].

Unsolved aspects of the problems. The use of soil and energy saving technologies is considered to be a rather pressing problem. In the next 15–20 years it is planned to implement soil protection technologies on a third of European countries' area. This is especially true for operations performed at a great depth. One option is to adapt the working surfaces of tillage machines to soil medium. Multi-stepped operating units sufficiently take into account the differentiated layers of soil conditions according to the tillage depth [2].

The protective properties of soils to a large extent are determined by the state of the top layer with the thickness of 0–5 cm. The presence of structural erosion resistant particles (> 1 mm) and preservation of plant residues are considered [3]. At the same time, obtaining high yields involves the intensification of primary tillage and creation of the optimal structure of its more powerful layer (5–20 cm).

In the operating units the use of multiple types of warping and crushing the soil are projected: breaking, splitting, separating, cleavage, crushing, bending, shearing and gravity blow [3]. Different methods have different degree of control and different energy consumption.

It is necessary to choose the most efficient way of handling the conditions and power capacity as the basis. Its use in the design of operating units of tillage machines, including deep soil scarifiers, can improve the basic quality indicators of the work.

To reduce the energy intensity of the process it is undesirable to utilize the processes characterized by pressing, clamping or compacting, i.e. splitting, breaking and offsetting.

Analysis of the recent research. The research on the operating unit surface shapes has been done with the purpose of tillage intensification with minimal energy costs [1]. Promising, from this point of view, is the application of varying load surfaces. The energy intensity of the processes of media destruction including soil is known to be largely determined by the degree of grinding. Needless grinding results in increased energy costs [2]. Operating units are acting on the soil by means of gradual bending in one or more coordinate planes [3]. It is necessary to consider two-dimensionality of soil medium and the cyclical nature of the soil crushing, the gradual destruction of larger prismatic-like units into smaller ones. The peculiarity of soil warping by bending is different resistance to compression and tension. The ratio of elastic modulus in compression and tension is $E_c/E_p = 2.5 \dots 4.1$ [3]. The imaginary neutral line of the ground floor under bending is displaced in the area of compression, resulting in up to 62–83 % of the soil in the cross section being under tension. This is a significant advantage of operating units with the preferred bending and stretching warps.

Objectives of the article. The project envisages the study of the influence of soil medium, parameters and placement of tillage units on energy intensity of soil destruction and creation of energy-efficient operating units of the excavation machinery.

In terms of controllability and differentiation of soil tillage, the priority ways are those which are more dependent on the parameters of operating unit than the characteristics of the soil medium, i.e. separation, breakage and bending.

Presentation of the main research. The basic idea of the project is that the tillage units are designed to be located in space so that each one works independently from another and develops the soil within the area determined by its ability to separate the largest volume of soil from the solid mass due to technical and technological requirements. However, the spaces in which the adjacent units work are joined. Working capacity of the operating unit is determined by its parameters, soil type, degree of coupling and additional loading (e.g. hydrostatic pressure) of the space.

In the course of theoretical research it is concluded that the process of deep differentiated tillage is efficiently performed with the use of the tiered operating unit. Its parameters enable to maximally take into account the differentiation of quality requirements to the tillage of arable and sub-arable soil layers. The main operating unit of such a multitier deep crusher is the curved soil-crushing surface. Due to the shape and parameters of the surface, the necessary quality of grinding of the developed soil layer is assigned [1, 3].

When loosening the soil it is necessary only to adjust its macrostructure without destroying the structural soil aggregates [3] that is why the design of potentially low-power deep tiller is to be based on the elastic soil properties with proportional relationship between stress and tensile warping. In this case the necessary condition is the stability of tensile strain rate of the lower fibre of soil chunks under its bending. Soil chunk is considered to be homogeneous by the density, continuous medium formed by a set of structural aggregates interconnected by the clutch forces. In structural ripping of soil (agriculture, reclamation) it is necessary to adjust only its macrostructure without destroying the structural soil aggregates.

Given these considerations, the authors have suggested different versions of multilevel operating unit shown in Fig. 1.

The version *a* has *V*-shaped placement of stands on the bearing frame for the best horizontal stability in operation. In oblique stands there is no vertical overlapping of working surfaces in tiers in the direction of movement of a working body. The soil developed perceives a cross bend and compression on working surfaces. For regulation of the dimple and stability of movement a reference wheel is set.

The version *b* has *A*-shaped placement of stands on the bearing frame for increase in coupling properties of the tractor from action of vertical response of resistance of the soil development. In oblique stands there is a vertical overlapping in 1/4 lengths of working surfaces at tiers in the direction of a working body movement. The soil

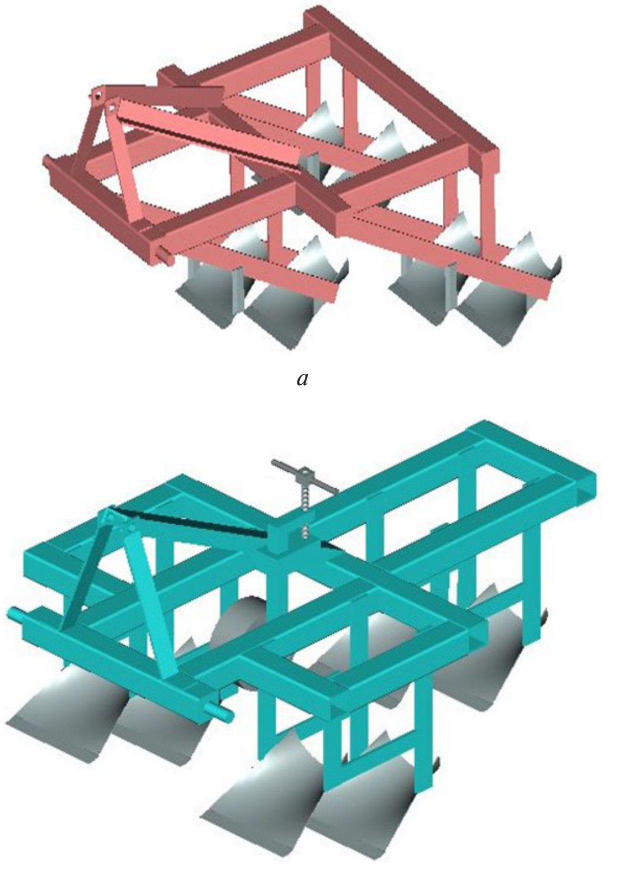


Fig. 1. Tiered operating unit for deep differentiated tillage:

a – V-like bearing stand placement; b – A-like bearing stand placement

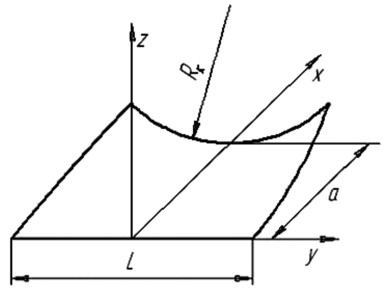


Fig. 2. Soil loosening surface:

R_k – the radius of the surface finite curvature; a – the length of the surface; L – the width of the surface

developed perceives only a cross bend without compression. In front of working surfaces in the upper tier vertical paper knives are set. The reference wheel is absent.

In general, the operating unit for deep tillage consists of a frame with bearing stands, on which the tillage tools in the form of conjunction of a horizontal knife with concave symmetrical channel surface of variable curvature are fixed (Fig. 2). The shape and parameters of the surface provide the required deformation, degree of tension and thus, crushing of the tilled soil layer.

Apparently, loosening the soil is due to bending warping. This is because the soil is bimodule environment. Therefore, when bent, as a result of correlation of compression and stretching modules, 62–67 % of active medium provides the tension, which is the least energy-intensive type of fracture.

The process of tillage is as follows. When the operating unit is moving, the soil particles which are cut off with every horizontal knife, are moving along the surface and are gradually bent from the edges to the middle due to the surface channel shape and are structured by warping bend in two coordinate planes reaching the estimates in the end of the surface (Fig. 2).

The use of these operating units enables, through the structure of the tilled soil, to establish favourable conditions for the recovery of the soil hydrophysical state without the use of additional technical means.

According to the research, the shape of soil loosening surface largely depends on soil conditions.

Multi-tiered operating units designed according to these principles were tested in production trials in Info-Centre CAE (Rivne region) and on arable lands of Mirne PGE (Rivne region) which have mainly sandy loam soil type with density of 1.41–1.48 g/cm^3 and humidity of 12–15 % at the depth of 0.5 m. The number of strokes of DorNDI drummer is 3...6.

The trials were conducted to test the efficiency of the operating unit and determine quantitative and qualitative indices of its performance.

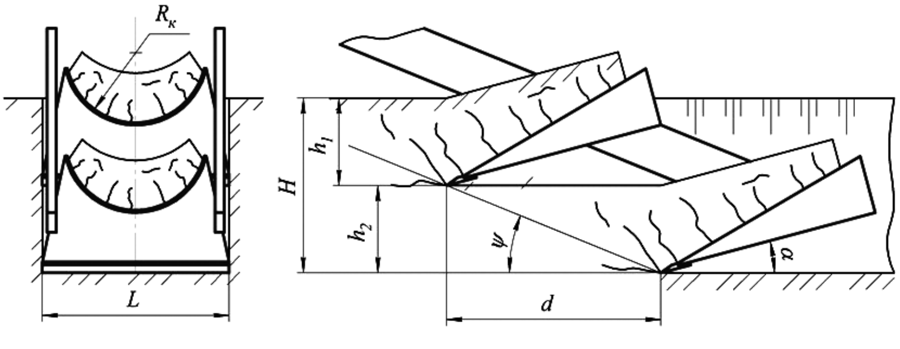
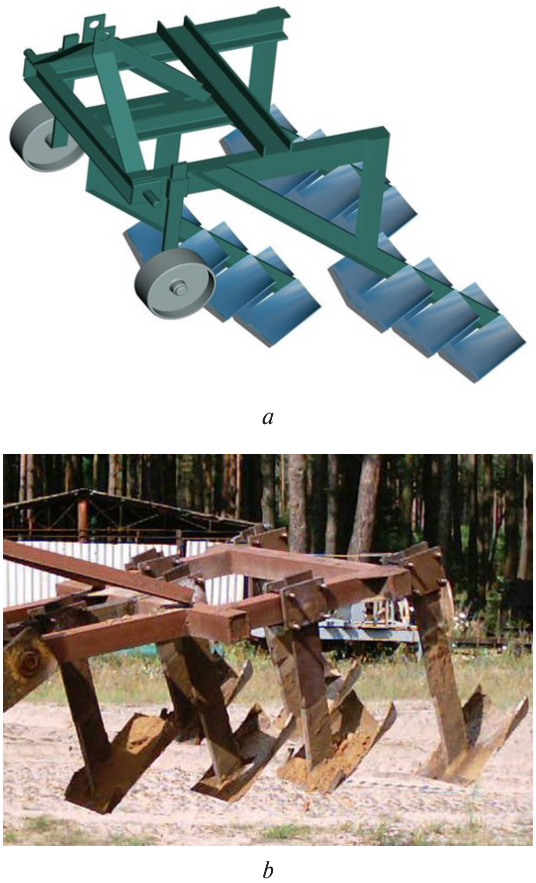


Fig. 3. Operating principle of the tiered operating unit for deep differentiated tillage:

R_k – the radius of the surface finite curvature; L – the width of the surface; H – the total tillage depth; h_1 – the depth of tillage by the upper tier; h_2 – the depth of tillage by the lower tier; ψ – the angle of the cutting edge line slope to the horizon; α – the angle of the surface to the horizon



a

b

Fig. 4. Tiered operating units for deep soil differentiated tillage with improved stands:

a – three-tiered with slanted blades; b – two-tiered with straight blades

The results of the tests revealed the following: deepening of the operating unit from the soil surface level was due to its own weight when hydraulic cylinders were in floating position and depth adjustment was carried out smoothly; soil loosening with multitiered operating unit is characterized by density decreasing to 1.11–1.28 g/cm^3 which corresponds to the loosening coefficient within 1.15–1.27; traction resistance was increasing proportionally to the tillage depth and averaged 25–28 kN; mixing of upper and lower layers of soil while loosening was not observed.

The comparative tests of two-tiered structures (Fig. 1) proved better efficiency in the performance of *A*-like operating unit with the surfaces where the main factor was just bending of soil layer. Installation of the support wheel made it possible to obtain better macrorelief of the field.

During testing of the first, *V*-shaped option, with surfaces where the main factor was just bending the soil layer, better field macrorelief was obtained. In the other option, the *A*-like type, with the surfaces with additional compressional destruction of soil layer due to the complicated passage of loosened soil, drawing prisms were formed before the operating surfaces, the surplus of which was running between the bearing stands forming undesirable field macrorelief.

In general, soil loosening by multitiered operating unit is characterized by the decrease in upper layer density to 1.22–1.36 g/cm^3, which corresponds to the loosening ratio within 1.23...1.32; in structural contents of loosened soil dominated the ground units to 25–50 mm in diameter (<25 mm – 65 %; <50 mm – 93 %); deepening of the operating unit from the surface was due to its own weight, and depth adjustment was smooth; mixing of upper and lower layers was not observed.

Besides some positive moments there was also little accumulation of soil between the paired stands.

Therefore, due to research studies on deep differentiated development of the soil it has been set that tier working bodies with unary stands (Fig. 4) are more perspective. At the same time placements of stands depends on soil type. For heavy soils the option with oblique stands is offered (Fig 4, *a*), and for light ones – it is constructive simple option with vertical stands (Fig. 4, *b*).

The main parameters of tiered operating units for deep soil differentiated tillage depend on soil conditions.

The maximum tillage depth is selected depending on the technological needs or physical and mechanical properties of soil horizons. If the soil is uniform, without any expressed illuvial horizons, the tillage depth of 0.4 ... 0.6 m is adopted. On the reclaimed lands with drainage systems, in order to improve their functioning, the depth of loosening is 0.15 ... 0.20 m lower than the depth of laying drains, counting from the top of drainage tubes.

That is

$$H = H_{dr} - d_{dr} - (0.15...0.2),$$

where H_{dr} is the depth of laying drainage; d_{dr} is the drainage tube diameter.

The angle of soil cutting with a plowshare is determined by the soil conditions

$$\alpha_p > 45^\circ - 0{,}5\varphi^\circ,$$

where φ° is the angle of soil internal friction.

Given that the angle of soil internal friction is 22° ... 30°, it is considered that $\alpha_p > 30...35^\circ$.

The vertical spacing of the soil loosening elements is defined as follows

$$h = \sqrt{\frac{2aB_{loos}q_{cr}h_c\left(1+\mathrm{tg}\,\varphi_0\,\mathrm{ctg}\,\alpha_c\right)}{\left(q_{cr}-q_0\right)k_{trans}\,\mathrm{tg}^n\,\alpha_a}}\times$$

$$\times\sqrt{\frac{1}{\left(1+\mathrm{ctg}\,\alpha_a\,\mathrm{tg}\,\varphi+\left(f_{on}-\varphi_{tool}\right)\left(\mathrm{ctg}\,\alpha_a-\mathrm{tg}\,\varphi\right)\right)}},$$

where α_c is the angle at the top of compaction core; α_a is the cutting angle; φ_{tool} is the coefficient of the tool carrier drive grip on the supporting surface; φ is the angle of the external soil friction; q_0 is the pressure on the knife upper surface; q_{cr} is the pressure on the face knife surface at the critical cutting depth; k_{trans} is the depth ratio of the guaranteed chipping of soil to the critical cutting depth ($k_{trans} = 0.9...0.95$).

The ratio of the tool carrier drive grip on the ground φ_{tool} and movement resistance f_{on} are selected according to soil conditions for the soil scarifier utilization and the type and condition of the drive; approximating rates *a* and n are defined by the appropriate method depending on the type of soil and its consistency (for solid sand clay $a = 1.564$; $n = 0.658$; for medium-soft loam, respectively – 1.654 and 0.593, stiff clay – 1.770 and 0.540; solid loam – 1.605 and 0.592, medium density clay – 1.659 and 0.581, hard clay – 1.616 and 0.589).

After that the number of the soil tilling tools in the stand is determined

$$M = H/h\,.$$

The tilt angle of the cutting part is defined from a condition

$$\frac{Bk_r - 2h\cos\alpha_a}{2h\sin\alpha_a} \le \mathrm{ctg}\,\alpha \le$$

$$\le k_{trans}(\mathrm{ctg}\,\psi + \mathrm{ctg}\,\alpha_a) - \mathrm{ctg}\,\alpha_a + \frac{S_2}{h},$$

where S_2 is selected in terms of strength rate; k_p is the coefficient of soil layer volume change.

The calculation of traction resistance required to move one stand with several soil scarifying tools is performed in the following way

$$W_{front} = \frac{H}{h} B_{loos} \left\{ k\ hA_3 \left(q_0 + \frac{(q_{kr} - q_0) hk_{trans}\,\mathrm{tg}^n\,\alpha_p}{2aB_{loos}} \right) + \right.$$

$$\left. + h_c A_4 q_{cr} \right\} + k_{ap}\gamma_s HB_{loos}^2,$$

where $A_3 = 1 + \mathrm{tg}\,\varphi\,\mathrm{ctg}\,\alpha_a + f_{on}(\mathrm{ctg}\,\alpha_a - \mathrm{tg}\,\varphi)$; $A_4 = 1 + \mathrm{tg}\,\varphi + \mathrm{ctg}\,\alpha_c$; for loosening loam $k_{ap} = 1.4$; $k_e = 0.9...0.95$; $k_{trans} = 0.9...0.95$; f_{on} is the coefficient of movement resistance; γ_s is the specific gravity of soil; k_e is the ratio of total power consumption of the cutting force; k_{ap} is approximation ratio of traction resistance of soil carrying.

The number of stands in the operating unit is determined according to the basic tool carrier traction rate

$$N_{ris} = \frac{W_{B.M}}{W_{front}}.$$

The methods are developed on the basis of research evidence and are used for determining the parameters of the stepped deep soil grinders with channel soil loosening surfaces. The main elements of the methods are tested at JSC "Rivnesilmash" [5].

The main criterion for designing the structure of deep soil scarifier is the value in cross-section of the structural unit l_w of the loosened soil which is set according to the recommendations [2, 4].

The radius value of the final cross-section surface R_e significantly affects the quality indicators of loosening. It is determined by the set size of the diameter of the structural soil unit and relative deformation of disruption (fissure) for respective soil conditions.

Quantitative indicators of the loosening strip depend on the width of the surface cutting edge L which is determined in proportion to the radius of the final cross section surface R_e.

The surface length a is responsible for the process of loosening intensity; it is determined depending on the operating speed of the loosening unit.

Longer surfaces are more linear than shorter ones contributing to easier passing of soil. In relatively long surfaces ($a > 0.25$ m for top soil layer, $a > 0.42$ m for subsoil layers) two-plane destruction takes place while in shorter surfaces it is three-plane destruction. Increasing the speed and improving soil jamming result in the surface extension.

According to the parameters of soil loosening surface the mathematical model $z = f(x, y)$ in the form of Cartesian coordinates is recorded.

Mathematical formulas for calculating the parameters of soil loosening surface are as follows

$$R_e = l_w\left(\frac{1}{2\varepsilon_r} + 1\right); \quad L = \frac{\pi}{2}R_e; \quad a = \sqrt{2\varepsilon_e \cdot L \cdot V_{ag} \cdot t_{1c}};$$

$$z = \frac{a}{x}(R_e - l_w) + l_w - \sqrt{\left(\frac{a}{x}(R_e - l_w) + l_w\right)^2 - y^2} \approx$$

$$\approx \frac{a}{x}R_e - \sqrt{\left(\frac{a}{x}R_e\right)^2 - y^2},$$

where ε_r is relative warping of the fissure; l_w is the size value of the calculated structural soil unit; V_{ag} is the operating speed of working unit; $t_{1c} = 1c$; z, y, x are the current coordinates; $y = 0...L/2$; $x = 0...a$.

The general assembly of the deep soil scarifier operating unit is determined by spacing of soil loosening surface in three mutually perpendicular directions.

The b value spacing of the tilling tools along the width of the operating unit is within the range limited to the principle of free soil passing between tiers without supporting of the upper tier by the lower one ($d_{\min}$) and avoiding the soil contact in the zone of active soil crushing ($d_{\max}$) which determines the stand inclination angle ψ.

Vertical spacing is determined by the height of the soil layer h that can be efficiently tilled with one surface.

The number of tiers j and stands m with soil loosening surfaces is determined by the total tilling depth H and the width of the cutting unit grip B.

Mathematical formulas for calculating the parameters of deep soil scarifier operating unit are as follows

$$b = 2h \cdot \mathrm{tg}\frac{\theta}{2};$$

$$d_{\max} = \frac{V_{ag}\cos\alpha_a}{2g}\left(V_{ag}\sin\alpha_p + \sqrt{2ga\sin\alpha_a + (V_{ag}\sin\alpha_a)^2}\right);$$

$$d_{\min} = \frac{h_2}{\mathrm{tg}\,\psi_2} - \sqrt{\frac{2R_v\cos\varphi(\mathrm{tg}\,\alpha_a + \mathrm{tg}\,\psi_2)}{L(q + C_q V_{ag})\,\mathrm{tg}\,\alpha_a\,\mathrm{tg}\,\psi_2}};$$

$$R_v = \frac{\cos^2\varphi_0 e^{(\pi + 2\varphi_0)\mathrm{tg}\,\varphi_0}\left(\frac{\gamma h_2}{2} + C\,\mathrm{ctg}\,\varphi_0\right)}{(1 - \sin\varphi_0)\cos\varphi_0} \cdot \frac{h_2}{\sin\psi_2}\left(\frac{\pi h_2}{\sin\psi_2} + L\right);$$

$$h = \frac{k_h + 1}{k_h}\frac{R_e}{36{,}23 \cdot e_n - 1{,}22} \le \frac{9kl_w(1 + k_h)\sin\alpha_a}{2\pi\sigma_p k_h};$$

$$\psi = \mathrm{arctg}\frac{h}{d}; \quad B = m(L + b) - b; \quad H = h \cdot j,$$

where θ, φ, φ_0 are respectively, the angles of cross section, external and internal soil friction, $\theta = 40{-}50°$; γ is the proportion of the soil in the natural state; h_2 is the depth of tillage on the lower tier; g is acceleration of gravity, $g = 9.81$ m/s^2; ψ_2 is the fissure angle of the soil in the lower tier, radian; q is the coefficient of the sizeable soil jamming, q = 120 000...150 000 кN/m^3; C_q is the coefficient considering the resistance change of soil bulk jam along with the speed change, C_q = 5.3 кN × s/m^4; k_h is the ratio of tension zone height to the compression zone height while bending ($k_h = h_p/h_c$); α_p is the angle of the surface installation to the groove bottom, α_r = = 15–30°; k is specific resistance to cutting in a tier; e_n is soil porosity; σ_p is limiting stress of the ground fissure; m stands for the number of stands with tilling units; j is the number of tiers.

Experimental testing and computer modelling of the given analytical dependencies for differentiated tiered loosening with different physical and mechanical soil characteristics proved the adequacy of the basic parameters of the suggested deep soil scarifier operating unit.

Conclusions. The developed technique for engineering calcula "Rivnesilmash" and CAE "InfoCenter" of Rivne region, provides the ability to create customized passive operating units for vertically differentiated deep soil tillage and land recultivation after opencast mining.

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Мета. Визначення параметрів конструкції ґрунтообробних органів для забезпечення енергозберігаючої розробки ґрунтів робочими органами машин для земляних робіт.

Методика. Теоретичні дослідження базувались на загальних положеннях землеробської механіки, елементах теорії суцільного середовища, теорії міцності Кулона-Мора. Аналітично-графічний аналіз математичних моделей виконувався за допомогою візуального їх відтворення у просторі та часі на ПЕОМ з використанням прикладних і розроблених програм.

Результати. Описані основні принципи створення адаптованих пасивних робочих органів для диференційованої по вертикалі глибокої розробки ґрунтів і рекультивації земель після добування корисних копалин відкритим способом (наприклад, бурштину).

Наукова новизна. Отримані математичні моделі для створення конструкції енергозберігаючих, екологічно спрямованих засобів розпушування й диференційованої розробки ґрунтів на основі встановлення закономірності механізму розпушення ґрунтової скиби двоплощинним згином.

Практична значимість. Розроблена методика проектування та інженерного розрахунку ярусного робочого органа для глибокої диференційованої розробки ґрунту.

Ключові слова: *робочий орган, ґрунт, подрібнення, ярус*

Цель. Определение параметров конструкции почвообрабатывающих органов для обеспечения энергосберегающей разработки грунтов рабочими органами машин для земляных работ.

Методика. Теоретические исследования базировались на общих положениях земледельческой механики, элементах теории сплошной среды, теории прочности Кулона-Мора. Аналитически-графический анализ математических моделей выполнялся с помощью визуального их воспроизведения в пространстве и времени на ПЭВМ с использованием прикладных и разработанных программ.

Результаты. Описаны основные принципы создания адаптированных пассивных рабочих органов для дифференцированной по вертикали глубокой разработки грунтов и рекультивации земель после добычи полезных ископаемых открытым способом (например, янтаря).

Научная новизна. Получены математические модели для создания конструкции энергосберегающих, экологически направленных средств рыхления и дифференцированной разработки грунтов на основе установления закономерности механизма разрыхления грунтового ломтя двухплоскостным изгибом.

Практическая значимость. Разработана методика проектирования и инженерного расчета ярусного рабочего органа для глубокой дифференцированной разработки грунта.

Ключевые слова: *рабочий орган, грунт, измельчение, ярус*

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