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Influence of design parameters of reclamation rippers on the improvement of agrophysical properties in treated soil

Victor I. Balabanov, Natalia B. Martynova*, Alexandr A. Makarov

Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, 49 Timiryazevskaya St., Moscow, 127434, Russian Federation

** Corresponding author's Email: nmartinova@rgau-msha.ru*

ABSTRACT

To create an optimal water-air balance of the soil, the ratio of the solid phase of the soil and the pore space should be approximately 1:1. This cannot be achieved without deep loosening, which makes its structure homogeneous and finely lumpy. Racks and V-shaped rippers do this type of work. The latter's advantage is high productivity and uniformity of the soil structure; the disadvantage is the increased traction resistance. To reduce traction resistance, it is necessary to determine the optimal parameters of the cutting angles of the ploughshare (studied from 10° to 45°), and side racks (studied from 13° to 24°), as well as the angle between the side racks (studied from 70° to 90°). Reducing traction resistance will increase productivity and drop energy consumption. The purpose of the research is to find the optimal parameters of the rack ripper. Experimental studies used a three-factor experiment with working organ models in laboratory conditions. The analysis of the results showed that the best parameters of the soil structure were obtained at a cutting angle within 30°-34°; in this case, the soil structure is homogeneous and finely lumpy. The lowest value of traction resistance is achieved at a lateral cutting angle of 13°-16° and an angle between the posts of 90°. The assessment was carried out using fractal methods. The conducted studies have shown that passive V–type rippers have competitive advantages over rack rippers when achieving the best indicators of loosened soil structure (soil density decreased by 28.8%, porosity increased to 43.4%). The creation of a working body with the studied angle parameters will reduce the traction resistance by 1.3 times.

Keywords: Deep soil loosening, Homogeneous soil structure, Quality of loosening, Rational parameters, traction resistance, Volumetric ripper.
Article type: Research Article.

INTRODUCTION

The earthworks are the most common and time-consuming work in constructing, operating, or reconstructing reclamation systems. The structure of the soil layer is determined by the granulometric composition, soil aggregation, and the mutual arrangement of soil particles and lumps, while to create optimal conditions for moisture and air exchange, the non-capillary porosity should be 55-60%. For sod-podzolic gley soils, with a ratio between the solid phase and pores of 1:1, where 25% of the total volume is occupied by air and 25% by moisture, the best conditions of soil regimes for agricultural plants are established (Barr *et al.* 2018). The structure of the arable layer can be adjusted by changing the density and structure of the soil. The fastest and most effective way to change the structure is regular treatment, the techniques of which increase the overall porosity, mainly increasing the volume of non–capillary pores, which in turn improves the water-air properties and enhances the microbiological activity of the soil (Drwish 2020). The most common and universal work method is the mechanical soil treatment by various working bodies (Jin *et al.* 2021). It aims to regulate and optimize the agrophysical properties of soils, such as structure, density, porosity, and structural condition (Edwards *et al.* 2016). It promotes the loosening of the treated layer and regulates the water-air and food regimes. As a result, more

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favorable conditions are created for the growth and development of plants. Deep soil treatment must meet modern quality requirements (Mari *et al.* 2015). The quality of the soil treatment depends on the design and adjustment of the machines and working bodies used. The technological or physico-mechanical properties of the soil, which determine the degree of loosening, crumbling, and compaction, significantly affect the processing quality (Bögel *et al.* 2016). Tillage affects the size of soil aggregates. The optimal size and mutual arrangement of soil aggregates ensure the best ratio of solid, liquid, and gaseous phase volumes. Structural soils retain a lower density for longer than structureless ones (Aikins *et al.* 2020). With deep loosening by the working bodies of deep soil excavators, loosening occurs – a change in the relative position of soil particles to increase the volume of soil and its porosity, as well as crumbling – a decrease in the size of soil particles and the division of the entire volume of the developed layer into smaller ones in the form of small lumps, lumps, structural aggregates (Barbosa 2020). According to the granulometric composition, sod-podzolic soil contains physical clay 28%, sand 39%, coarse dust 33%, medium and fine dust 17%, and silt 11% - the primary name of the granulometric composition of such soil is light loamy. The aggregate of various sizes, shapes, and compositions determines the soil structure, and the structure determines the process of their formation. In the process of soil decomposition, structural aggregates can form a lumpy structure – lumps of more than 10 mm (large –lumpy - more than 100 mm and small–lumpy 10-100 mm); macrostructure - 0.25-10 mm and microstructure – less than 0.25 mm (Ahmagi 2016). The water-physical characteristics of soils depend on the soil structure. The soil structure improves the physical and mechanical properties of the soil, as well as increases the erosion resistance of soils (Snezhko *et al.* 2023). With an agronomically valuable soil structure, a rational combination of capillary and non-capillary porosity is formed. In structuring, the soil is first mechanically divided into aggregates, which then combine to form soil lumps. At the same time, the forming structure is influenced by physico-mechanical, physico-chemical, and biological factors (Milkevych *et al.* 2018). Deep tillage significantly affects the formation of the soil structure, which, together with the formation of soil separations, causes their destruction (Song *et al.* 2022). Deep loosening allows the reduction of the density of the soil, but over time, it gradually increases to a certain constant value – the equilibrium density characteristic of a certain soil. The optimal density establishes the best ratio of capillary and non-capillary well volumes, the maximum amount of water available to plants with a sufficient degree of aeration. The difference between the equilibrium and optimal densities determines the intensity and depth of tillage, respectively, the greater it is, the more often and intensively it is necessary to carry out mechanical processing (Martynova *et al.* 2020). According to Godwin (2007), the optimal density for different soils is about 1.1-1.3 g cm^{-3}. Sandy and sandy loam soils have a wider density range, while clay and loamy soils a smaller one. Regulation of soil density during deep processing helps to increase moisture reserves in the autumn, winter and spring periods while preventing surface runoff and the manifestation of water erosion. During structuring, the content of capillary suspended water in the soil increases (Salar *et al.* 2021). When justifying the regime for regulating moisture reserves in the root layer of structureless soil, an important element is the range of their change, which depends on the water-physical parameters of the soil and the biological properties of the crops grown. In clay soil, the physical ripeness of the soil is in the range of humidity 50-65% total moisture capacity of the soil in loamy and sandy loam: 40-70% total moisture capacity of the soil (Ramadhan 2014). For ripe medium loamy sod-podzolic soil, the agrotechnical moisture range of ripe medium loamy soil is within 12-21% of the mass of absolutely dry soil (Mari *et al.* 2015). According to some studies, the optimal soil moisture should be within 60-65% of the total moisture capacity of the soil, for medium loamy soil: 70...75% of the total moisture capacity of the soil (Chen *et al.* 2013).

The use of deep loosening: Non-dumping deep loosening of the soil without formation turnover is the most effective method of improving the unfavorable physical properties of soils and their hydrological regime, promotes the transformation of surface runoff into the subsurface, increases the active porosity of soils, their filtration, deeper penetration of plant roots, elevates the capacity of the fertile layer of reclaimed soils, as a result of deep loosening, the yield of crops increases by 30% or more (Da Rocha *et al.* 2016). Deep loosening and crumbling of loamy and clay soils with a filtration coefficient of less than 0.3 m/day is a mandatory agro-reclamation measure. The main parameters of deep loosening are depth, width, intervals, direction, completeness of loosening, the amount of loosening and uniformity of loosening of the treated volume of soil, and the formation of soil separations: fractions of various sizes depending on the technological and physicomechanical properties of soils. This caused the creation of many rippers of various purposes and designs, parameters, and other indicators. Passive rippers are the most widely used for loosening durable soils up to and including category 3. Passive rippers have canine or toothtype working bodies with ploughshares mounted at the ends of the racks. Along with rack rippers, chisel plows, and slot-mole rippers, previously commercially available in separate batches, passive action rippers with a V-shaped working body of the type RG: 1.2; RG: 0.5; RG: 0.8 are known. The V-shaped rippers of the RG -0.8 type developed at the All-Russian Scientific Research Institute of Hydraulic Engineering and Melioration named after A.N. Kostyakov consists of a ploughshare and two racks inclined at an angle to the horizon of 45°, the ploughshare has a loosening angle of 30°, a rear angle of 10°, for loosening soil in a stream, an inclined rack is made with a kinematic angle the points are 30° (Balabanov *et al.* 2023). The width of the grip is 3.3 meters (Al-Suhaibani & Ghaly 2010). When working, the rippers are supported by wheels. By reinstalling the wheels, the depth of travel is determined, and the working bodies are hung on a standard rear agricultural suspension. Field tests of looseners conducted in the Moscow region on soils of category 2 to a depth of 0.5 – 0.6 meters showed a fairly high productivity – 3.0 ha h^{-1} when aggregated with a K – 701 tractor, the soil loosened by 30-40%, and its surface was evenly raised by 20-25 cm (Behera *et al.* 2021). Deep reclamation loosening completely replaced the dump plowing that was carried out on these lands. Rippers of this type allow in one pass to loosen the entire volume of soil along the width of the capture without turning the formation to a depth of up to 0.8 m, depending on the type of compaction, cultivated crops, soil type with productivity greater than that of rack rippers by 2-5 times (Da Rocha *et al.* 2016). The coefficients of loosening and completeness of loosening are not inferior or higher than those of rack rippers by 1.05 and 1.5 times, respectively (Fechete-Tutunaru *et al.* 2019) They minimize loose zones at the bottom of the furrow with the same grip width as the rack rippers (Mehrez *et al.* 2014). An analysis of the operation of these rippers showed that they have significant disadvantages – they require large traction forces, unevenly loosen the layer in depth - they form 16% of soil aggregates over 200 mm on the surface, requiring additional grinding (Inshakov *et al.* 2022). Therefore, rippers of this type are of particular interest from the point of view of improving the design of the working bodies of rippers (Li *et al.* 2019). The conditions of the interaction between the working bodies of rack and especially volumetric rippers with the soil differ significantly from the working bodies of earthmoving machines, namely: blocked cutting, greater depth, increased soil density of the lower layers, requirements for a certain degree and completeness of loosening (Makange *et al.* 2021). The processes of cutting by knife working bodies and cutting perimeters of excavator buckets, working bodies of agricultural machines have been studied in more detail (Askari *et al.* 2016). As shown by experimental studies of cutting forces with a volumetric ripper, the values obtained differ from the calculated values recommended for profiles of excavator buckets. The difference in results is more noticeable with an increase in the loosening depth (He *et al.* 2016). The increasing loosening depth can explain this; the nature of soil deformation by the frontal surface of the working organ changes (Marakoğlu *et al.* 2021). In the upper zone, directly adjacent to the daytime surface, the working body interacts with the soil of an already disturbed composition, where crushing, shifting, and bulging towards the surface of the soil mass occurs (Bulgakov *et al.* 2019). Starting from a certain depth, the soil is subjected to periodic compression, followed by its separation from the mainland. The influence of the exposed surface of the massif on the stressed state of the soil gradually drops as the depth increases.

MATERIALS AND METHODS

To study the process of soil deformation during loosening and to study the effect of some parameters of the volumetric ripper on the transformation of the basic agrophysical properties of the soil, the formation of soil structure and traction resistance, a set of experiments was performed on a soil channel with models of the working bodies of passive rippers. During the experiments, the influence of the parameters and design of the working bodies of a volumetric ripper on the energy and quality indicators of the loosening process and changes in the agrophysical properties of the soil were studied. To assess the energy and kinematic characteristics of the loosening process, the traction force was determined by the strain gauge method. The kinematic parameters were estimated by the amount of movement of the soil layers up and forward along the movement of the working body and by the method of layer-by-layer marking of layers with colored chalk. Studies of models of working bodies were carried out on loamy soil, which before each experiment was compacted to 4 blows of the density meter of the Scientific Research Institute of Road Construction. It was corresponded to a density of 1.75 g cm^{-3}, the relative humidity of the soil in various series of experiments ranged from 9-22%, the processing depth was 18 cm, which in terms of nature was 0.72 m. The repeatability of each experiment during the studies was at least 4-5. During the experiments' preparation, the soil was brought to a homogeneous state by loosening, necessary moistening, leveling, and compaction. Soil moisture was determined by weighing a soil sample before and after drying. Then, the soil was leveled and compacted. After preparing the soil, a model of the working body was installed on the trolley in the desired position, and then experiments were carried out. Experimental studies were carried out on models of working bodies with different cutting angles of the ploughshare - α and side racks - β, as well as the angles between the racks of the racks – γ. To determine the effect of the main angles on the quality and resistance to loosening, a 3-factor experiment with regression analysis of the results was performed. Several variants of models of working bodies of rippers were made for research. The scale of the models based on approximate physical modeling was chosen 1:4. The design of the ripper models made it possible to change the cutting angles of the ploughshare and side racks. Physical models of the working bodies of volumetric rippers with various parameters were designed and manufactured. In preparation for the 3-factor experiment, variable factors were selected and the limits of their variation were determined, the minimum and maximum values of the angles were α: from 10° to 45°, β: from 13° to 24°, γ: from 70° to 110°. Parameters such as humidity, soil density, and loosening depth were kept constant. Following the theory of experimental planning, a regression equation was compiled linking the parameter under study with all the factors affecting it. In addition, the significance of each factor was assessed, and the less significant one was excluded from further studies. The traction force of the working body was chosen as an optimization parameter.

In general, a mathematical description of the process can be represented by a dependency:

$$Y=f(X_1, X_2, X_3), \quad \textbf{(1)}$$

where Y is a dependent variable or response function, i.e. force F, X_1, X_2, X_3 are independent variables affecting Y, i.e., α, β, and γ, respectively.
The upper ($W_{i\ max}$) and lower ($X_{i\ min}$) levels are set for each factor. The average value of the factor, the base level (X_{0i}), with the range of variation $D_{Xi} = X_{imah} - X_{0i}$.
When planning the experiment, the dimensional independent factors X_i were transformed into dimensionless Z_i, normalized:

$$Z_i = \frac{(x_i - x_{0i})}{\Delta x_i}, \quad \textbf{(2)}$$

In this case, we get $X_{imax} = +1$ *u* $X_{imin} = -1$
The number of experiments *L*, in which all possible, different combinations of levels of all factors are realized, was determined by the formula:

$$L=K^m, \quad \textbf{(3)}$$

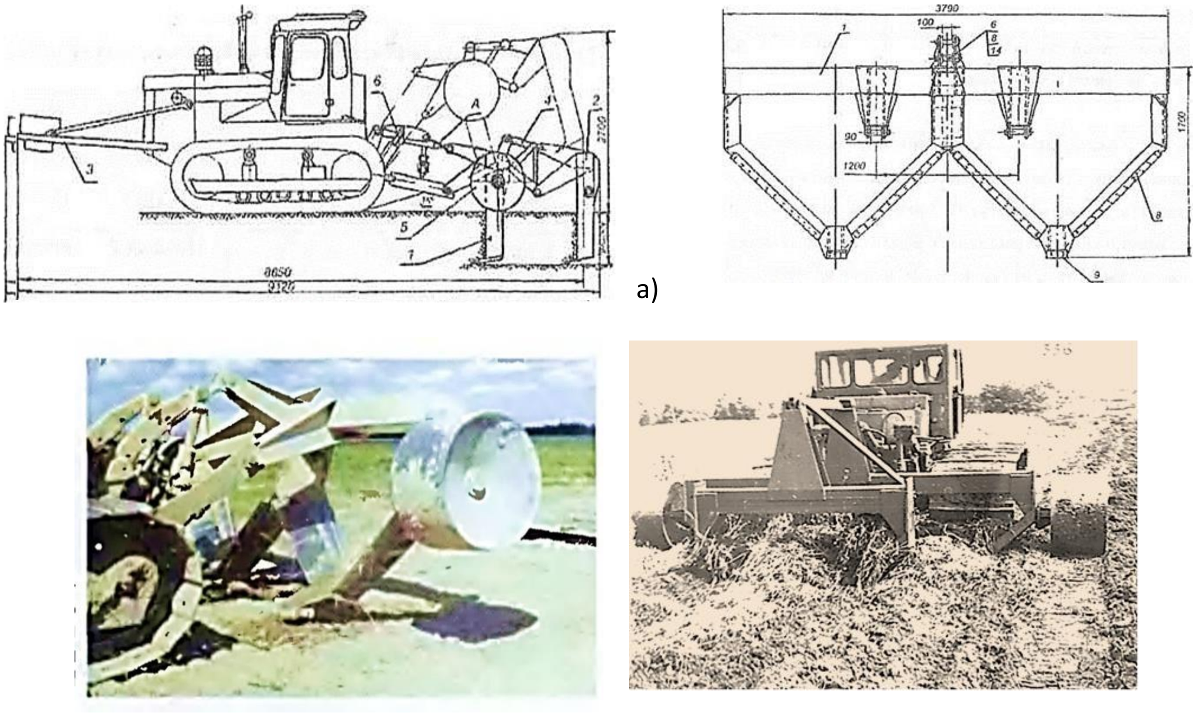
where: *m* is the number of factors, *K* is levels.
The experimental results can be preliminarily represented by a linear regression equation of the type:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3, \quad \textbf{(4)}$$

where: *Y* – evaluation of response function values, b_0, b_1, b_2, b_3 – estimates of the coefficients of the regression equation.
For a comparative assessment and clarification of the dependence of the studied power and technological parameters, one-factor experiments of models of working bodies with cutting angles from 10° to 45° were carried out. During the experiments, the nature of the deformation and destruction of the soil was studied. The parameters of the loosened soil were measured including: the lifting of the soil prism by the working body between the side posts (h_1), the height of the loosened soil above the initial surface (h_2), the length of the propagation of soil deformation in front of the working body (Ldef), the movement of the topsoil along the course of movement (Lperem), soil density at different depth of loosening (h), the sizes of soil aggregates on the surface and over the entire depth of loosening were estimated.

RESULTS AND DISCUSSION

To justify the choice of parameters and design of a volumetric ripper (Fig. 1), the condition of a combination of two factors was fulfilled: a lower traction force is possible with sufficient uniformity of soil fractions of a certain size over the entire depth of loosening (Fig. 2).



b) c)

Fig. 1. V-shaped ripper RG- 0.8: a) general view of the machine; b) type of ripper in two-body design in the transport position; c) type of ripper in three-body design during the working position (compiled by the authors).

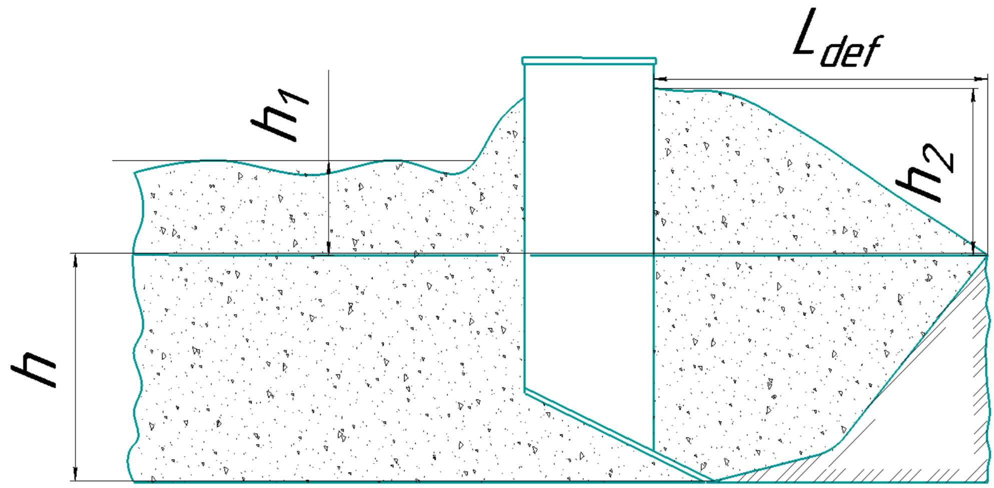
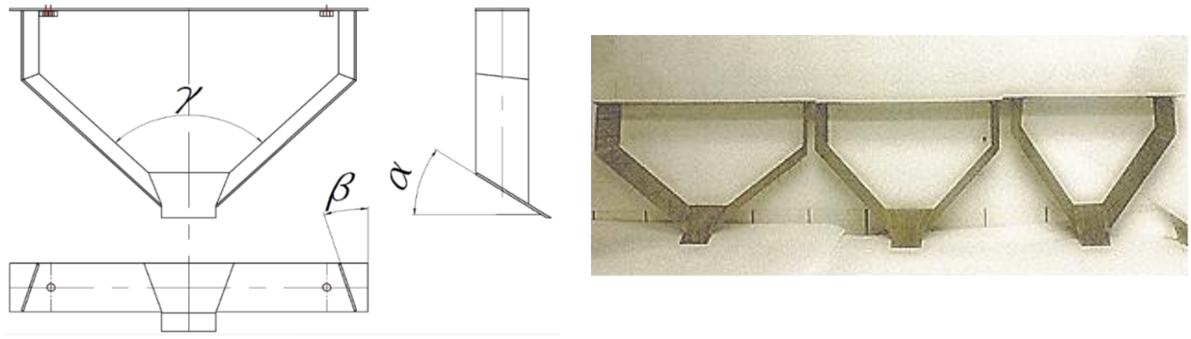


Fig. 2. Loosened soil parameters (compiled by the authors).

In previous studies, the foundations were laid for the use of deep rippers as a reclamation measure to increase drainage water flow (He *et al.* 2016; Balabanov *et al.* 2023). These works do not justify the design and parameters of the working equipment of a volumetric ripper, and an assessment of the quality of loosening and the influence of the ripper parameters on the basic agrophysical properties of the soil after loosening is not given (Mehrez *et al.* 2014; Barbosa 2020). To study the effect of the design parameters of the reclamation ripper on the agrophysical properties of the cultivated soil a set of sequential experimental studies was conducted in several stages (Milkevych *et al.* 2018; Behera *et al.* 2021). To justify the choice of cutting angles and inclination of the side racks, a 3-factor experiment was conducted with models of working bodies with straight side racks (Fig. 3). To this end, a set of sequential experimental studies was conducted in several stages (Al-Suhaibani & Ghaly 2010; Makange *et al.* 2021). To justify the choice of cutting angles and inclination of the side racks, a 3-factor experiment of models of working bodies with straight side racks was conducted (Fig. 3).



a b

Fig. 3. Working body of a volumetric ripper: a - angular parameters of the ripper; b - models of the working body (compiled by the authors).

According to the results of the experiments, a functional dependence of the traction force was obtained for variable parameters of the cutting angles of the ploughshare α, side racks β, and their tilt angles γ in physical terms:

$$F= -22,8-0,33\alpha+4,4\beta-0,7\gamma-0,067\alpha\beta+0,033\alpha\gamma \quad \textbf{(5)}$$

The analysis of the equation showed that the cutting angles of the working body of the ripper have the greatest influence on the magnitude of the pulling force. The angle of inclination of the racks γ affects the force to a lesser extent. To clarify the effect of cutting angles on the technological, qualitative, and power parameters of the loosening process, one-factor experiments were carried out (Fig. 4). It can be seen from the graphs that with an increase in the cutting angle, the resistance increases for models of working bodies with tilt angles of 70 and 90, and decreases for a working body with an angle of inclination of the side racks 110. This can be explained by the degree of interaction zones between the side posts (Bögel *et al.* 2016; Bulgakov *et al.* 2019). With an increase in the slope of the side racks, the width of the grip increases, and therefore a larger volume of soil is processed, which leads to high energy costs. Considering the working process of loosening, each element of the working body can be represented as a wedge located in space at certain angles (Fechete-Tutunaru *et al.* 2019; Li *et al.* 2019). The nature of soil deformation under the action of a wedge mainly depends on its geometric parameters and soil properties. In the process of loosening, a part of the soil is separated, having a trapezoid shape in cross-section, and a force effect on a certain volume of soil in front of the working body, which leads to a displacement of the soil up and forward, accompanied by its deformation. The soil, moving relative to the surface of the wedge at a speed, simultaneously moves perpendicular to the upper plane of the wedge, resulting in a shift and crumbling of the soil layer. Comparative results allowed us to determine the parameters of loosening, such as the propagation of deformation during longitudinal and transverse sections, the movement of soil up and forward, and the nature of the surface depending on different angles. The deformation parameters were set. When loosening in front of the working body, the soil rises and collapses, a volume is formed in the form of a convex shell, the lower plane of which is bounded by a curve in shape close to a parabola (Fig. 5). The length of the propagation of the deformation (Ld) in the form of a prism-shaped like a "shell" in front of the working body was 0.9-1.1 of the loosening depth (h). The height of the soil rise h_2 between the side posts was 0.75 h, after the passage of the working body it descended to the surface, forming a strip of loosened (swollen) soil height h_1, amounting to 0.2-0.3 h. Longitudinal sections of the loosening zone showed that the destruction of the massif during deformation occurs from the cutting edge of the ploughshare, then spreads forward and upward with a more intensive rise along a curved trajectory upward to the soil surface, connecting with a parabolic curve bounding the segment of the soil prism above the initial surface. The analysis of the research results showed that the values of the lowest traction forces of 0.71 kN have a ripper model with angles β = 13° and γ = 90°. For ripper models with an angle of γ = 70°, the increase in traction was from 0.83 to 0.88 kN with a change in the cutting angle, which is associated with more intense compression and lifting of the soil between the side posts. For models with an angle of γ = 110°, the highest values of traction were obtained from 1.05 kN to 1.32 kN, which is associated with an increase in the width of the working body and the volume of the loosened soil. The highest height of the swollen soil (h_2)

was observed for the ripper model with angles β = 24°, and γ = 90°, while the spread of deformation in front of the working body and the amount of movement of the upper soil layer along the course of movement were 1.1-1.9 times less than for models with angles γ = 70° and 110°.

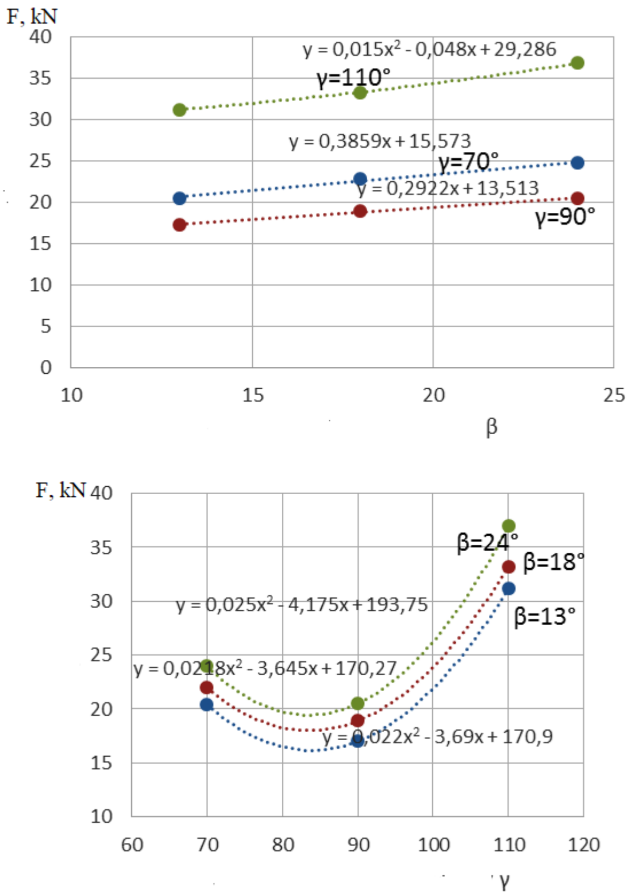


Fig. 4. Dependence of the traction force on the cutting angles of the side racks (compiled by the authors).

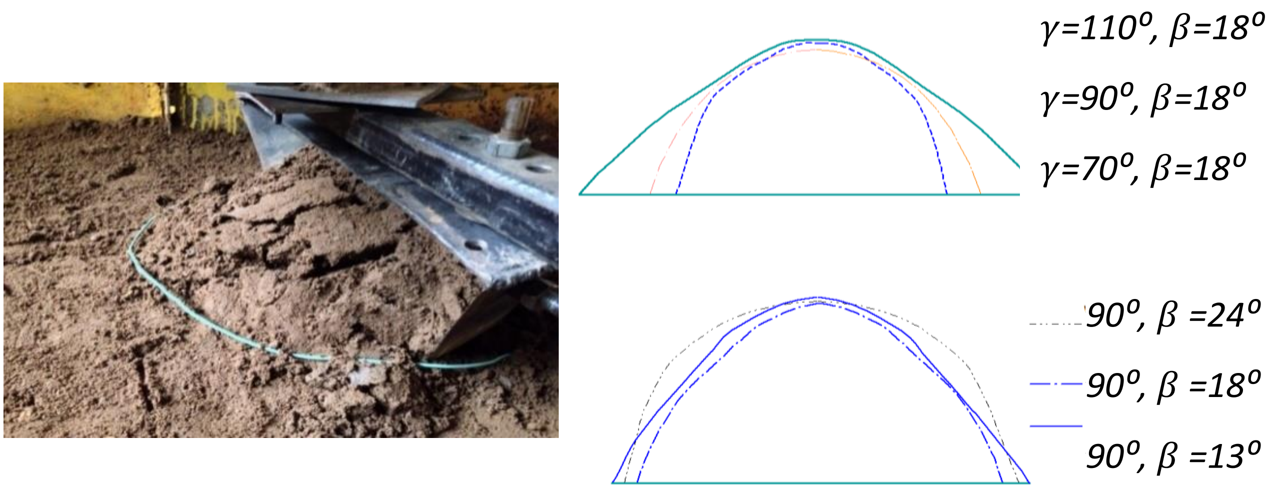
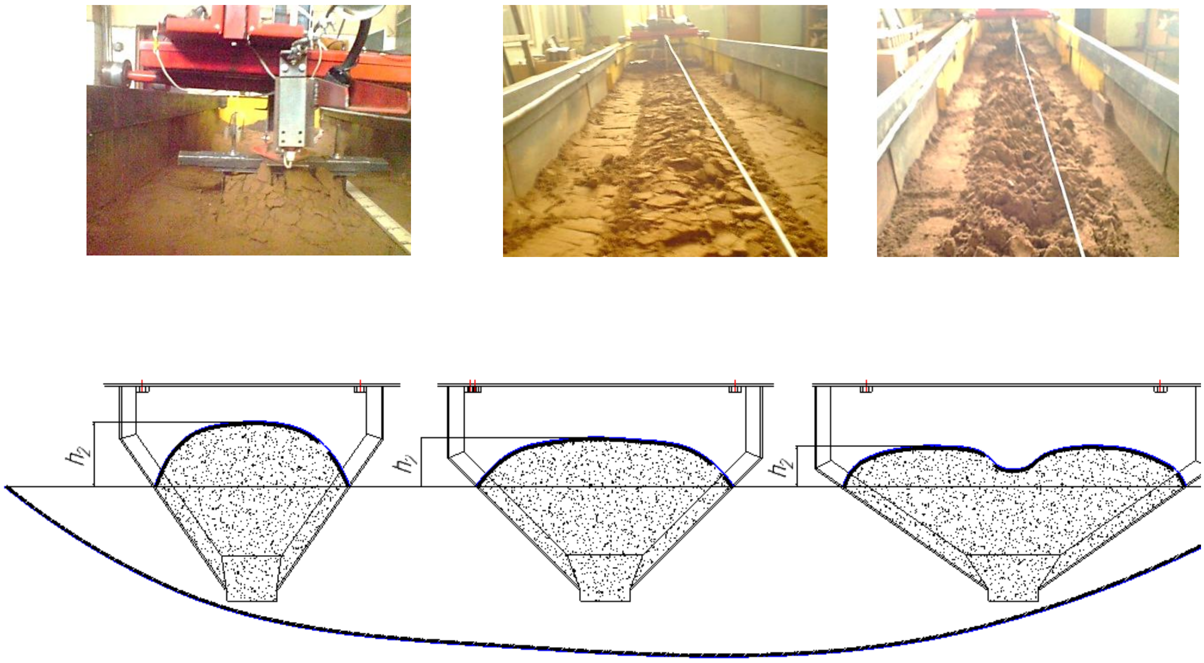


Fig. 5. The shape of the soil deformation in front of the working body of the volumetric ripper: a - curves limiting the soil deformation zone for rippers with different angles γ, at an angle β = 180; b - the nature of the deformation in front of the rippers, with different angles β at an angle γ = 90° (compiled by the authors).

The height of the swollen soil for the model of the working body with an angle of γ = 110° was 1.5 times less than for the model with an angle of γ = 90°, while a hollow equal to half the height of h_2 was formed in the middle of the strip of loosened soil (Fig. 6). This can be explained by the fact that the side struts were located at a considerable distance from each other and affected the treated layer without mutual influence. Based on the data on the values of traction forces, specific loosening resistances $K_d = F_t/A$, kN m^{-2} were obtained. The lowest value of K_d = 15.43 kN m^{-2} was obtained for the ripper model with angles γ = 90° and β = 13°. By an increase in the cutting angle of the posts β, a slight elevation in the specific resistance to loosening was observed. The specific energy consumption for this model was the lowest and amounted to 2.65-2.88 kW m^{-2}. The specific loosening resistance of the Cud for models with an angle of γ = 70°, according to the average values, turned out to be 1.36 times greater than for models with γ = 90°, the specific energy consumption is 1.46 times greater. For ripper models with angles γ = 110°, the specific loosening resistance at different cutting angles of the side racks was intermediate and varied from 17.8 kN m^{-2} to 22.4 kN m^{-2}.



a b c

Fig. 6. Lifting of the treated soil above the initial surface: a - models of the working body of the ripper with angles γ = 70°; b - γ = 90°; c - γ = 110° (compiled by the authors).

To assess the degree of crumbling, the average sizes of soil aggregates of loosened soil were measured on a loosening strip 1 m long. Histograms of the size distribution of soil aggregates showed that the most uniform distribution with a predominance of smaller aggregates was when the model was working with angles γ = 90° and β = 13°-16°. The results of experimental studies also made it possible to establish the dependence of the traction force on the loosening depth at different values of the cutting angle of the ploughshare. The analysis of the distribution of the fractal dimension of the soil before and after loosening was also carried out. The higher the value of the fractal dimension, the more the structure is developed, and, consequently, more loosened. Using this analysis, the choice of the cutting angle of the ploughshare is justified (Fig. 7). The fractal dimension increases at the cutting angles of the ploughshare from 25 to 35, which means that the greatest loosening of the soil occurs at this interval. In the center of the loosening zone, the values are higher than at the edges, which means that the soil is heterogeneous, and the larger the area is covered with cracks and voids. With a further increase in the cutting angles of the ploughshare from 40 to 50, its decrease is observed, which means that the soil is not uniformly loosened enough.

The dependence of the dispersion of the fractal dimension on the cutting angle of the ploughshare has a pronounced power-law character with a following regression equation:

$$D = 2 \cdot 10^{-5} \alpha^2 - 0.001 \alpha + 0.0327 \qquad \textbf{(6)}$$

The dependence of the traction resistance on the cutting angle of the ploughshare can be represented by the following equation:

$F = 0.0242\alpha^2 - 1.3505\alpha + 41.441$ **(7)**

Experimental studies with ploughshares of various shapes have shown that the lowest energy indicators were obtained for a working body with a convex-concave shape of the working surface compared with the rectilinear shape of the working surfaces – the traction force decreased by 17.7%, the specific energy intensity by 15.6%, and the loosening coefficient of $K_r = 1.3$. However, the highest loosening coefficient was obtained when testing a working body with a convex shape of the working surface: $K_r = 1.34$. In all models of ploughshares with different surface shapes, the force value differed slightly (no more than 5-7%), and the average values of fractions with sizes from 5 to 10 cm (the most recommended requirements) prevail. Moreover, by a concave and convex-concave shape of the working surface of the ploughshare, the size distribution is more uniform and the largest number of small fractions. The amount of lifting of the loosened soil above the initial plane when testing ploughshares with curved surfaces had a higher height compared to a straight wedge. A comparative analysis of the results shows that ploughshares with curved surfaces contribute to a greater degree of loosening. Based on the analysis of the research results, the most rational values of angles can also be recommended α = 30°-34°; β = 13°-16°; γ = 90°, lower values – for denser soils. Nevertheless, the analysis of the uniformity of loosening showed that in some experiments individual fractions up to 100 mm in size were observed in an amount of about 5-10%, which requires additional grinding. Further research was carried out to select a more rational design of the ripper, which provides better grinding. Due to the redistribution of subsurface runoff in the process of deep loosening, due to changes in the physical properties of the soil, and an increase in the overall borehole, the moisture content of the root layer is optimized (Table 1).

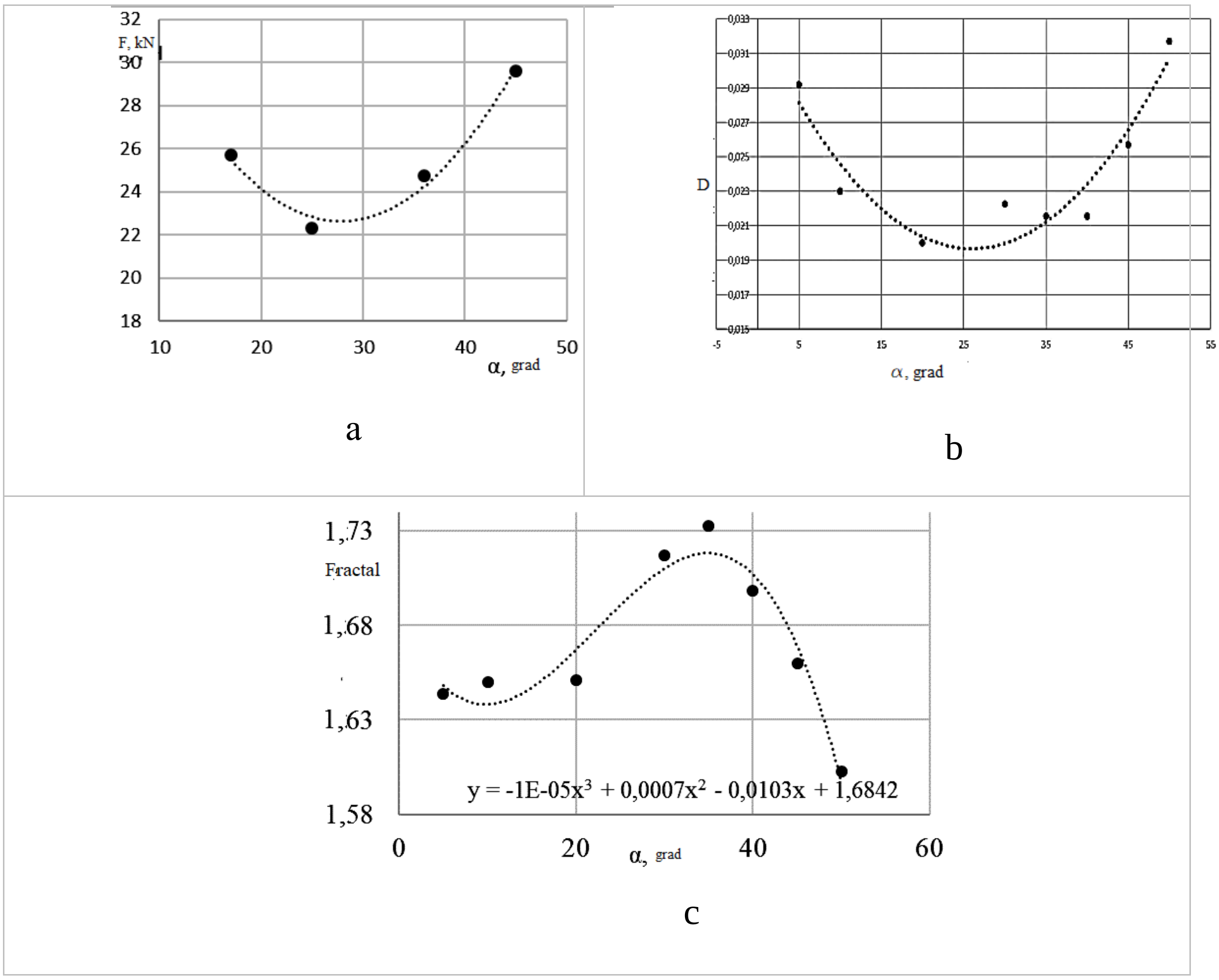


Fig. 7. Graph of the dependence of the cutting angle of the ploughshare on: a - on the pulling force; b - on the dispersion of the fractal dimension; c - fractal dimension on the cutting angle. The results of fractal analysis confirm the results of previously performed studies on the selection of the most rational angles (compiled by the authors).

Table 1. The main parameters of the loosened soil condition after loosening (soil type - medium loam; compiled by the authors).

Soil layer, cm	Average density		Porosity		Full moisture capacity		The lowest moisture capacity	
	(g sm^{-3})	From the average density (%)	(%)	Increases from average porosity (%)	From the volume (%)	From the average value (%)	From the volume (%)	Increases from the average value (%)
0 -10	1.32	5	51.1	7.8	47.4	14.2	34.5	1.6
11-20	1.29	6	52.74	14.7	42.0	4.0	34.3	1.7
21-30	1.36	7.4	50.5	13.8	43.3	11.0	34.3	1.8
31-40	1.37	12.7	51	21.4	43.0	12.5	29.9	2.4
41-50	1.33	21.3	50	43.6	39.5	8.2	27.2	2.3
51-60	1.36	23.6	50.1	42.3	44.0	10.0	24.7	1.3
61-70	1.32	27.5	51.6	60.1	38.0	8.5	22.2	1
71-80	1.38	28.8	49.6	69.8	29.0	1	21.1	1

In the process of deep loosening, the pore space of the soil increases due to changes in the interaggregate porosity, the intra-aggregate porosity changes slightly, while partial mixing of the upper humus layer with the lower layers occurs. As a result, there is a significant increase in the filtration coefficient of C_f, especially in the sub-arable horizon of 40-70 cm.

CONCLUSION

As a result of multifactorial experiments, empirical dependences were obtained that allow taking into account the angular parameters of the working body when determining the traction force. A real picture of the kinematics of soil particles in the flow with volumetric soil compression and movement of the working body is obtained, which allows us to establish the mutual position and numerical values of the movement of soil layers in the direction of movement depending on the depth of loosening (L = 1.06-1.2 h), which is commensurate with the depth of loosening. The energy costs of lifting and moving the soil mass are justified. As a result of the 3-factor experiment, the regression equation was obtained: $F = -84.05 + 1.4\alpha + 1.9\beta + 0.48\gamma$, which allowed us to determine the rational cutting angles: $\alpha = 30^o$-34^o, $\beta = 15^o$-18^o, lower values – for heavy and large – for light loams, as well as γ = 90o at the lowest tractive effort F.

A set of one-factor experiments made it possible to justify the most rational cutting angles and installation of side racks and a plowshare, at which the best loosening uniformity and the least effort were observed.

Assessment of the degree of loosening by fractal analysis methods made it possible to more accurately assess the degree of loosening and obtain fractal characteristics of loosened soil for working bodies with different designs and parameters under certain working conditions to select the most rational ones. Based on the analysis of the distribution of the fractal dimension of the soil before and after loosening, it was found that the most uniform loosening of the soil was observed at the cutting angles of the ploughshare α = 30-34°, β = 15-18°; γ = 90°.

Loosening of sub-arable horizons contributes to the redistribution of water reserves, and interception of vertical groundwater flows, which are for soils of natural composition (q = 190 m^3 ha^{-1}), and loosened soils (up to 250 m^3 ha^{-1}). A study of the articles on the water balance in potato cultivation on sod-podzolic gley soils showed that replenishment of moisture reserves is required in almost all growing seasons (from 450 to 800 m^3 ha^{-1}), excluding wet years.

Carrying out deep volumetric loosening of over-compacted gley soils allows to reduce soil density to 28.8%, increase porosity to 43.4%, and increase water capacity by 8.3 -12.5%. The change in the water-physical properties of the soil leads to an improvement in agrophysical properties and, as a result, to an increase in crop yields

Contribution of the authors. All authors of this study were directly involved in the planning, execution and analysis of this study. All authors of this article have read and approved the submitted final version.

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