Parameters of deep chiseling of soil

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Abstract. The article covers materials related to the value of soil density and the method of its reduction, deformation, the choice of depth and technology of loosening the subsurface horizon, as well as the determination of some parameters of the loosening leg. One of the optimal ways to reduce the density of the soil is its two-tier chiseling, with the least resistance of the soil to the movement of the tool, with a stroke depth of the working bodies of the upper tier = 0.2.

1. Introduction
Among the complex agro-technical measures aimed at increasing the fertility of packed soil by high-quality mechanical destruction of packed subsurface horizon, optimal conditions are created for plant growth and crop accumulation. The negative consequences of packed soil are diverse: the water-air regime of the soil and the conditions of mineral nutrition of plants deteriorate, the yield of agricultural crops decreases, soil erosion increases, and the effectiveness of fertilizers decreases [1-4].

2. Main part
2.1. Soil density
The value of soil density is very large and versatile. The choice of soil cultivation methods, and, consequently, the selection of tools in order to create a cultivated arable and subsurface horizon, is mainly determined by the density of the possibilities of using the corresponding complex of soil cultivation methods.

The density of the soil is strongly expressed both in the arable and subsurface horizons [5, 6]. In addition, with the annual shallow plowing of the soil to a depth of 0.3 m, it led to the formation of a dense layer, which is called the “plow bottom” and extends to a depth of 0.4 - 0.45 m. The density of the subsurface horizon of the soil of old irrigation reaches 1600 - 1700 kg/m$^3$, and the porosity decreases by 5 - 6%, in comparison with the soil of the arable layer.

The packed subsurface horizon negatively affects plant growth and the yield of raw cotton. At the same time, the infiltration of water into the subsurface layers is very difficult, therefore, the moisture reserves in the soil decrease, the air exchange in it deteriorates and, in general, the nutrition of cotton deteriorates and the yield decreases. When the density of the subsoil horizons is 1200 - 1300 kg/m$^3$, the root system develops in favorable conditions, deforms little, does not compress, bends less (figure 1) and is covered with lateral processes along the entire length [7-8]. At the same time, the root system is able to use the nutrients and water of the subsurface horizon fully.
2.2. Study of soil deformation
In the process of loosening, the soil is destroyed within a certain volume, the width of which on the surface of the field exceeds the width of the loosening element.

Study of soil deformation depending on the main parameters of the loosening leg: on the crumbling angle $\alpha$ and the width of the loosening leg $b_L$ was carried out in laboratory-field conditions using painted beds [9].

On the longitudinal sections, the longitudinal plane of cleavage A-A is visible, and on the transverse sections, the direction of the lateral plane of cleavage of the soil B-B is obtained.

A formula was obtained that characterizes the dependence of the angles of longitudinal $\psi_1$ and lateral $\psi$ cleavage of the soil on the angle of crumbling of the loosening leg $\alpha$, i.e.

$$\psi_1 = 0.04\alpha^2 - 2.6362\alpha + 76^\circ 39'$$
$$\psi = 0.01\alpha^2 - 1.63\alpha + 83^\circ 55'$$

By calculating these dependencies, taking into account the change in the crumbling angle, it was found that with an increase in the angle $\alpha$, the angles of longitudinal and lateral shearing of the soil decrease.

A decrease in the angle of longitudinal shearing leads to an increase in the zone of propagation of soil deformation in front of the leg. This area defines the attachment point for the support wheel on the ripper chisel frame. If the support wheels are attached to the frame inside the crumple zone, then they will fall into the soil, and the set depth of travel of the loosening share will not be sustained. At the same time, the loosening depth increases from the specified one, which leads to an increase in the traction resistance of the ripper chisel. Therefore, the support wheel must be installed outside the zone of propagation of soil deformation.

Change of leg width $b$ from 0.4 to 0.7 m (at $\alpha = 20^0$; $L = 0.9$ m) did not lead to a significant change in angles $\psi_1$ and $\psi$. 

Figure 1. Development of the cotton root system depending on the density of the soil: 1- irrigated grey desert soil, 2- old-plow of old irrigation, 3 old-irrigated meadow, 4- old-irrigated meadow-takyr.
Figure 2. Cross section of a field with colored soil layers.

Figure 3. Longitudinal deformation of the soil by a loosening leg.

Figure 4. Lateral soil deformation by a loosening leg.

Figure 5. Scheme for determining the soil deformation zone.

2.3. The depth of soil chiseling

The depth of soil chiseling depends on the thickness and depth of loosening of the packed layer. Common seals are conventionally divided into (figure 6): upper (in the layer of the arable horizon); plow bottom 1 (in the layer below the arable horizon); compaction of the subsurface 2 (in the layer below the plow bottom).

The plow bottom is called the compaction of the soil in the layer located below the passage of the blades of the working bodies of the implement. It starts immediately after the boundary of the processed layer. The thickness of the plow bottom layer can be 12 – 17 sm in some cases it reaches 20 cm [10].

Chiseling, as the most energy-intensive operation, is this non-moldboard tillage with tools mounted on the frame loosening legs, with undercutting of the seam along the working width, which is carried out periodically on soils with an over-consolidated subsurface horizon at a given depth - up to 50 cm. Hence, in experiments [11-13] with loosening legs of the same width and with the same crumbling...
angles, the linear dimensions of the lateral extensions $b_b$ up to a certain limit of the loosening depth, increases approximately proportionally, which remains between the full depth of the slot and the depth of its expanding part. Further deepening of the working body does not increase the loosening zone (figure 7), since below the so-called “loosening depth” ($h_p$) a zone of soil displacement is formed in the form of a gap, the width of which is equal to the width of the loosening leg $b$.

The main reason for the phenomenon of the critical depth of chiseling, which turns out to be the boundary of the zones of process modifications - loosening and cutting with separation of shavings, is the compressibility of the soil under load. At the same time, the efficiency of deep chiseling of the compacted subsurface horizon deteriorates.

![Figure 7. Scheme for determining the critical depth.](image)

The critical depth of loosening depends on the amount of soil chipping from the sides and the crumbling angle of the working body and the physical and mechanical properties of the soil [14].

$$h_k = \frac{b_o \cdot \cos(\alpha + \varphi)}{\mu_0 \cdot \cos \left( \frac{\alpha + \varphi + \rho}{2} \right)}$$  \hspace{1cm} (1)

By calculating the formula (1), with the values $\alpha = 20^0$, $\rho = 40^0$, $\varphi = 25^0$ and $\mu_0 = 0.76$ we determine that $h_k \approx 0.37 m$. At this critical depth, only the plow bottom can be destroyed. With deep chiseling of the soil in the cotton-growing zone, not only the plow bottom is destroyed, but also the lower subsurface is also necessary to loosen up. Therefore, the calculated critical depth is not sufficient.

2.4. Technology of chiseling of the subsurface horizon of the soil

Due to the high energy intensity of the technological process, deep loosening of the subsurface horizon cannot be combined with two-tier plowing, i.e. [6] it is carried out before (option II) or after plowing (option I) (figure 8), as well as two-tier chiseling of the subsurface horizon (option III).

Option 1: 1) plowing the soil to a depth of 0.3 m, 2) loosening of arable land to a depth of 0.5 m.
Option 2: 1) loosening stubble to a depth of 0.5 m, 2) plowing a loose soil layer to a depth of 0.3 m.
Option 3: Two-tier chiseling of the subsurface horizon.

When loosening the subsoil according to options I and II, the tractor makes two passes in the field for each option, and one pass according to the third option. Naturally, in this case, according to the first two options, the costs of loosening the subsurface horizon are higher than according to the third option.
However, the third option can be carried out in sandy fields or in fields littered with stones, that is, where plowing the soil is ineffective.

![Diagram a)

![Diagram b)

![Diagram c)

Figure 8. Soil shear force at different loosening technologies: a) loosening arable land (option 1); b) loosening the stubble (option 2); c) two-tier chiseling (option III).

The sequence of loosening the subsurface horizon is not significant influence on the yield of raw cotton. However, there is a significant difference between the energy performances of tools for different technologies of their use.

The energy performance of implements for various technologies of their use is characterized by the determination of the traction resistance of the plow and the ripper chisel.

For this purpose, we use the formula of V.P. Goryachkin.

\[ F = fG + Kab + \varepsilon \sqrt{ab} \]  

(2)

Then, the total energy consumption for the options consists of the traction resistance of the plow \( F_n \) and the ripper chisel \( F_p \), i.e.

\[ F_1 = F_n + F_p \]  
\[ F_2 = F_n + F_p \]  

(3)

Where: \( F_1; F_2 \) - respectively, the total traction resistance when loosening arable land and when plowing a loose layer (option 2).

Internal forces of mutual attraction link soil particles. Therefore, the strength and deformability of the soil are determined by the properties of the particles and the bonds between them. Mechanical destruction of the soil should be considered mainly because of overcoming the internal bonds between particles, which consist of forces that depend on moisture, density and pressure on them. In this case, it is necessary to take into account the heterogeneity of the soil. Due to the difference in size, shape, density, moisture content, as well as the strength of their bonds, destruction proceeds in a complex way. After the pressure on the soil reaches a certain critical value, the bonds are destroyed not immediately throughout the entire zone of the load, but gradually.

The mechanical strength of the soil determines the value of resistance to destruction (deformation). The greater the density of the soil in depth, the greater should be the efforts for deformation and lifting
of the layer, as well as the forces of inertia. Plowing leads to disruption of the connection between soil particles of the arable horizon, therefore, the force due to soil deformation will be only in the subsurface horizon, and the resistance due to the mass and inertia of the soil layer in both horizons. During layer-by-layer cultivation, due to the difference in the density of the soil in the upper disturbed arable layer and in the lower destroyed subsurface horizon, the efforts due to the mass and inertia of the soil layer will not be equal.

Table 1. Traction resistances of tools with different sequence of their use.

| Sequence of application of tillage tools                                      | Traction resistance of implements, kN |
|------------------------------------------------------------------------------|--------------------------------------|
| Two-level plowing of the soil to a depth of 0.3 m + loosening to a depth of 0.5 m | 18.8  39.1                           |
| Loosening the soil to a depth of 0.5 m + two-tier plowing to a depth of 0.3 m  | 12.4  56.4                           |

The total cost of processing a strip with a width of 1 m in the first variant was 46.87, and in the second is 52.48 kN, due to the greater energy intensity of the ripper chisel when working on stubble than on arable land. The traction resistance of the ripper chisel when working on arable land is 39.9 kN, and 57.5 kN on stubble. This is because when loosening the soil before plowing, the tractive effort is directed mainly at deformation of the soil and lifting the layer with loosening legs, in addition, with an increase in the resistance of the implement, the slipping of the tractor increases.

The lower energy consumption of the main soil cultivation with the use of a ripper chisel according to the first option allows increasing the working speed of the units and thereby increase productivity.

With two-tier plowing, lumps of more than 50 mm in size are 2-2.5 times smaller than when loosening the soil. This is due, firstly, to the lack of a chisel ripper in a more overdried part of the soil. The quality of soil crumbling when loosening arable land is better (lumps larger than 100 mm) is 8.5% than when loosening solid soil is 11.1%. This is because the plow layer does not turn out during loosening, but rises slightly by the plowshares of the loosening paw.

The undercarriage of the machine crushes large lumps formed during plowing. In addition, when plowing a loose layer, due to the rotation of the layer, large lumps are turned inside out onto the surface of the field. Therefore, according to the option of plowing a loose layer, there are low indicators for the quality of crumbling, compared with loosening arable land.

2.5. Substantiation of the depth of travel of the working body of the upper tier with two-tier chiseling of the soil

In the area of irrigated agriculture, gray soils in terms of texture are sometimes medium and heavily loamy with the inclusion of crushed stone, which are located in the 0 - 0.3 m horizon (III option, figure 8). Due to the light texture on desert sandy soils, a dense layer does not form in the arable horizon. The lower horizon from 0.4 to 0.5 m is strongly compacted, where the soil density reaches 1.6 - 1.7 g/sm³. On such soils, the processing of the upper layer by the rotation of the seam and the destruction of the lower horizon can be replaced by two-tier loosening. With two-tier soil chiseling, the depth of travel of the working bodies of the upper tier in relation to the lower tier is determined depending on the energy performance of the chisel tool, which consists of soil resistance to the movement of the working organs of the upper and lower tiers, i.e.

\[ F = F_b + F_w \] (4)

The working bodies of the upper tier work in conditions of a blocked cut, the central working body of the lower tier in conditions of an unblocked one. Two side-working bodies of the lower tier work in a semi-free cut. Taking into account the above and the forces acting on the soil layer, we determine the efforts \( F_b \) and \( F_w \).
\[ F_b = A_b \left[ \frac{K_4^1 \cdot \varepsilon_1}{\sin \psi_1} + \gamma_2 \left( \ell \varepsilon_2 + \frac{v^2}{g} \right) \right] + n_b \cdot F_{cb} \]  
(5)

\[ F_u = A_u \left( \frac{K_4^1 \cdot \varepsilon_1}{\sin \psi_1} + (\gamma_1 A_b + \gamma_2 A_u) \alpha_b + n_u F_{eu} \right) \]  
(6)

Where \( A_b \), \( A_u \) - the area of chiseling of the soil, respectively, of the upper and lower tiers, which are determined by the formulas:

\[ A_b = n_b (b h_b + h_b^2 \text{ctg} \psi) \]  
(7)

\[ A_u = n_u b h + h^2 \text{ctg} \psi + (n_u - 1) \left[ h - \frac{(2t - b)}{4} \right] \text{tg} \psi (2t - b) - A_b \]  
(8)

Where \( K_4^1 \), \( \gamma_2^1 \) - soil resistivity to shear and the density of the arable horizon, \( F_{cb} F_{eu} n_b n_u \) - accordingly, the resistance of the soil to the movement of the racks and the number of working bodies of the upper and lower tiers, \( t \) - inter-tracks of the post.

\[ \alpha_b = \ell \varepsilon_2 + \frac{v^2}{g} \]  
(9)

An analysis of the obtained formulas shows that both the area \( A_b \) and \( A_u \) (at \( h = 0.5 \) m) depend on the depth of loosening of the upper tier \( h_b \). Therefore, with an increase in depth \( h_b \) from 0.1 to 0.4 m, the area \( A_b \) increases from 0.0556 to 0.3937 m\(^2\), and the area \( A_u \) decreases from 0.76 to 0.437 m\(^2\). At the same time, the zone of propagation of soil deformation in the upper tier increases, and in the lower tier it decreases, which leads to an increase in the effort caused by deformation. The effort \( F_c \) depends on the arrangement of the working bodies of the upper and lower tiers of the implement, as well as the depth of soil loosening by the working bodies of the upper tier.

Figure 9. Change of forces \( F_H \), \( F_b \) and \( F \) depending on the depth of the stroke of the upper tier.
For example, the theoretical minimum resistance of the soil to the movement of the tool, with its two-tier chiseling, was obtained at the depth of the stroke of the working bodies of the upper tier \( h_b = 0.2 \).

### 2.6. Arrangement scheme and track width of chisel legs

Working bodies with an inter-track spacing must be placed on the implement frame so that they are not clogged with soil and plant residues when processing the soil to the maximum depth. The fulfillment of these requirements mainly depends on the correct placement of the working bodies on the implement frame.

Based on the deformation of the soil when working at a greater depth, the distance between adjacent furrows should be greater than when working at a shallower depth; an indispensable condition that determines the required distance between the working bodies in the transverse direction is that there should not be untreated strips between adjacent furrows and there should not be soil jamming in the space between the racks of adjacent paws in each row, i.e. the width of the overlap when the adjacent paws are acting on the soil should be less than the distance \( t \) between adjacent legs in the same row, and the height of the ridge should not exceed that allowed by agricultural demand and its width at the base should be minimal. The width of the soil deformation zone from the lateral sides of the loosening paw is generally determined by the dependence.

\[
B = b_L + 2h_p \cot \psi
\]  

(10)

If the loosening legs are located in the same row, then in order to carry out continuous processing and prevent clogging of the tool with soil, they must be placed at a distance \( t = L = B \). However, the distance \( t \) is not enough: the tool is clogged with plant residues, satisfactory crumbling of the soil is not achieved, large ridges remain at the bottom of the furrow, the height of which reaches the depth of loosening. One of the ways to increase the width of the track spacing is the arrow-shaped arrangement of the working bodies on the implement frame in two or more rows.

![Figure 10. Soil deformation.](image)

The arrow-shaped scheme, with the arrangement of the working bodies in a straight line directed at a certain angle to the direction of movement of the unit, allows leaving a large space between the working bodies along the working width. As a result, free passage of the cultivated soil and plant residues along the implement is provided with a sufficient track-to-track width and a certain outreach of the legs relative to each other. In addition, a significant advantage of the arrow-shaped scheme is that it allows reducing the number of working bodies working in a blocked environment. To prevent clogging of the working bodies of the soil and plant residues, when placing them according to the arrow-shaped pattern, it is necessary to correctly select the outreach of the legs \( L_p \) along the course of the unit and the opening angle of the arrow-shaped frame \( 2\gamma_p \). When arranging the working bodies in a straight line at
an angle to the direction of movement, the outreach of the loosening legs can be determined by the formula:

\[ L_p = h_p \cdot \text{ctg} \psi \]

(11)

The opening angle of the ripper chisel frame is determined by the formula

\[ \text{ctg} \gamma_p = \frac{h_p \cdot \text{ctg} \psi}{b_p + 2h_p \cdot \text{ctg} \psi} \]

(12)

From formula (20) it can be seen that the opening angle of the arrow-shaped frame depends on the loosening depth, the width of the loosening paw and the angles of the longitudinal and lateral soil shearing. So, at \( h_p = 0.2 \) m and \( b_p = 0.2 \) m, the opening angle of the arrow-shaped frame is \( \gamma_p = 53^0 \). The grip width of the loosening leg, depending on the opening angle of the arrow-shaped frame, is determined by the formula (12).

\[ b_p = \frac{h_p \cdot K \cdot \text{ctg} \psi - 2h_p \cdot \text{ctg} \psi \cdot \text{ctg} \gamma_p}{\text{ctg} \gamma_p \cdot K} \]

(13)

The analysis of the formula shows that by decreasing the angle \( \gamma_p \), the width of capture of the loosening paw also decreases (table 2).

**Table 2.** The width of the grip of the loose claw.

| Leg capture width, m (\( b_p \)) | The opening angle of the arrow-shaped frame, degree |
|----------------------------------|-----------------------------------------------|
| 0.33                             | 53                                            |
| 0.20                             | 45                                            |
| 0.102                            | 37                                            |

However, an excessive decrease in the angle \( \gamma_p \) leads to a lengthening of the frame and thereby to an increase in the mass of the implement. Therefore, the opening angle of the arrow-shaped frame is taken within 45 - 55 degrees.

Given the permissible ridge height, we find the distance:

\[ t = b_p + 2h_p \cdot \text{ctg} \psi \]

(14)

At \( b_p = 0.2 \) m, \( h_p = 0.07 \) m, distance \( t = 0.31 \) m, and inter-track width is \( L = 0.62 \) m.

### 3. Conclusion

The density of the soil is strongly expressed both in the arable and in the subsurface; extending to a depth of 0.4 - 0.45 m the soil is gradually enriched with nutrients, which leads to an increase in its fertility. The quality and energy intensity of loosening the subsurface horizon of the soil primarily depends on the perfection of the technological process of work, the design of tools for moldboard-free tillage.

The mechanical strength of the soil predetermines the value of the resistance to destruction. The greater the density of the soil in depth, the greater should be the efforts for deformation. The lower energy intensity of the main tillage with the use of a ripper chisel after two-tier plowing allows increasing the working speed of the units and thereby increases productivity.

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