Modeling the Process Of Interaction Of Loosening Organs With Soil

Feruza Alimova[1], Mukhayyokhon Saidova [1]

Feruza Alimova[1], Mukhayyokhon Saidova [2]
m.saidova87@mail.ru , feruza.alimova.1961@mail.ru

Abstract

The article presents data on the simulation modeling of the technological process of soil loosening, which helps to increase the accuracy of assessing the efficiency of soil-cultivating units, analyzing the energy intensity of the process and choosing optimal loosening modes. The aim of the study is to determine the distribution of stresses, deformations and soil resistances on the working bodies of a two-tier ripper. Key models for determining soil porosity, plasticity, resistance to deformation and hardness are considered. Using the COMSOL Multiphysics application software package, a simulation model of the soil in the process of its interaction with the working parts of the tool was created. A calculation scheme for the problem of soil loosening with a two-tier ripper is presented using the COMSOL application software package. According to the results of the study, the highest values of the projection of the main stress are observed in the direction Oy, and in other directions they are negligibly small; on the ridges of the two-tier ripper they are the same and distributed evenly. The results of the study of the stress-strain state of the working bodies and soil during loosening were obtained, critical zones in the design of the working bodies were determined, which will increase their wear resistance and durability with further optimization of the parameters of the tillage tool.

Key Words: *soil-cultivating, working bodies, energy, modeling.*

Introduction

Improvement of design and operational parameters of machine and tractor aggregates must be carried out through joint research of systems operating in conjunction with each other, while taking into account their dynamic operating modes, environmental conditions, and technical and operational parameters of the aggregates. A detailed analysis of the technological process of soil cultivation, determination of agrotechnical and energy indicators of a soil-cultivating tool is possible when developing a model of the process of interaction of its working parts with the soil.

The main parameters that must be taken into account for an adequate representation of the soil cultivation process model are the design of the soil cultivation tool and the physical and mechanical properties of the soil

It is known that when working bodies act on the soil, elastic and plastic deformations occur simultaneously in it, both in the cut layer and in the displaced soil particles. These processes are closely interconnected and form a single system of soil cultivation.

Various authors have used systems analysis to analyze various processes [1; 2; 3]. Successful implementation of these processes requires the development of new technologies and new working bodies. The physical and mechanical properties of the soil have a significant impact on the agrotechnical indicators and traction resistance of soil-cultivating machines.

Soil as a technological environment is characterized by parameters that change in time and space; the physical and mechanical properties of the soil change depending on weather conditions, crop rotation, application of fertilizers to the soil, etc. Analysis of the research shows that the study of soil deformation under the impact of tillage tools is possible by analyzing the nature of soil deformation under the impact of a wedge. A deep analysis of the relationships between the design of tillage working bodies and the efficiency of the tillage process is given in the works [4, 5, 6]. According to classical agricultural mechanics, the main part of the working bodies of soil-cultivating implements is considered as a type of dihedral or trihedral wedge [7, 8].

In the works of researchers [9, 10], the connections between the geometric parameters of the modeled surface and the agrotechnical and technological parameters of the working element were determined based on the analytical method of constructing the surface by L.V. Gyachev. Applying the theory of soil deformation, scientists considered

the stresses in the soil layer under the action of a group of forces along the profile of the working element as discrete quantities, i.e. as the sum of the stresses from the action of individual forces. Models of soil destruction are constructed taking into account the structure of the soil environment, the variability of mass, its deformation and destruction.
The rheological model of a Newtonian viscous fluid was also used as a soil model, which made it possible to simulate the processes of deformation and movement of the soil, as well as to study the phenomena occurring within the massif [11]. Such studies were conducted using the FiowVision software package. Currently, when developing a mathematical model of the soil cultivation process, scientists use the discrete element method [12, 13]. It has been established that the Hertz-Mindlin contact models taking into account adhesion and cohesion are suitable models for describing the type of connections between soil particles.
For modeling using the discrete element method, the main physical and mechanical properties of soil particles were established, namely Poisson's ratio, coefficient of static friction, shear modulus, Young's modulus, and particle density. The developed mathematical models allowed us to represent the process of mechanical tillage, determine the traction resistance of a tillage machine under various parameters, study the stress-strain state of its working parts and soil, and the nature and direction of soil movement during tillage.

Soil properties are divided into physical: soil density (ρ), which is classified as density in the natural state (ρ_n), true density of soil particles ((ρ_s) and dry soil ((ρ_d); humidity (W), porosity (n), specific gravity of soil (γ);
and mechanical: compressive strength - expresses the ability of the soil to resist destruction under load; shear strength (angle of internal friction and adhesion), the angle of internal friction (φ) and cohesion (c) determine the resistance of the soil to shear; the deformation modulus (E) describes the ability of the soil to elastic deformation under load; the compressibility coefficient (m) characterizes the change in the volume of the soil under pressure [14].

Materials and Methods

The process of developing new working bodies, as well as optimizing design and technological parameters, is based on mathematical models and the obtained regularities. The process of soil cultivation is always unstable due to changes in the actual depth of cultivation and the physical and mechanical properties of the soil, wear of the working element and its individual elements, and other factors. Identifying the nature of the interrelations of factors that contribute to increasing the efficiency of soil-cultivating aggregates, and developing working bodies to ensure optimal results at all stages of the soil cultivation process under changing soil conditions are urgent scientific tasks.
The management of the soil cultivation process consists of obtaining the necessary indicators based on the knowledge of the parameters of the working element, the cultivation method, the method of cutting and loosening, the properties of the technological environment, by regulating the operating mode of the system. They must comply with agrotechnical, environmental, operational and safety requirements.
The following are accepted as input parameters of the loosening process as a system: soil properties, design of the tillage tool and working bodies, method of fastening the working bodies to the frame and to each other; location of the cultivated area on the slope.
The main output parameters are the parameters of the stress-strain state of the soil and the structure of the unit, the distribution of longitudinal and vertical stresses, and critical zones in the design of the working bodies.

Results and Discussion

In mechanical tillage in agriculture, various mechanical models are used that describe the interaction of the soil with the working parts of agricultural machinery. These models help to predict soil resistance, tool forces, energy intensity of processing and the quality of the work performed. In soil science, soil mechanics and agrophysics, there are a number of mathematical models for determining the porosity, plasticity, resistance to deformation and hardness of the soil: calculation of soil properties using the Mohr-Coulomb criterion (the relationship between soil porosity and density); Proctor's model for soil hardness (relationship between compaction and soil moisture); V.P.Goryachkin's classical model of general soil resistance based on the balance of forces and soil deformation [15, 16].
Let's look at the key models for each of these properties.
Relationship between soil porosity and density

$$P=1-\frac{\rho_b}{\rho_s},$$

where: ρ_b - soil density (volumetric), ρ_s - soil solid density

ρ_s = 2,65…2,75 g/cm3.
Proctor's model for soil hardness. The relationship between compaction and soil moisture is quadratic:

$\rho_b = A + BW - CW2$,

where: *A,B,C* - coefficients determined experimentally.
Soil failure model (Mohr-Coulomb) - soil is considered a plastic material that fails by shear:

$\tau = c + tg\varphi$,

where: τ - shear stress, c - cohesion, φ - angle of internal friction.
Determines the limiting state of the soil when interacting with the tool. Used to calculate the forces of interaction between the ploughshare and the soil. Resistances to cutting, friction and shear are taken into account.
Dependence of forces on the angle of attack and speed
:

$R=\sigma \cdot A+\tau \cdot l \cdot R,$

where: R - resistance, σ - normal voltage, A - contact area, τ - shear stress, l - contact length.
For a given soil the following parameters are known: specific cohesion c = 25 kPa; angle of internal friction φ = 30^0; normal stress σ = 50 kPa.
It is necessary to calculate the shear stress τ, at which the shift will occur, and check the stability of the soil under a given load. Substituting the known parameters, we obtain: τ = 53.85 kPa; soil density ρ_b = 1.3g/cm3; b = 1,3 g/cm3.

Clay content: C=40%; Specific adhesion: c=30 kPa; Friction angle: φ = 25^0; Humidity: W = 15%; a = 10; b = 0,5; k = 0,1.
Optimal humidity. For pre-sowing treatment:

$$W_{onm} = \frac{a+b\cdot C}{1+k\cdot\rho_b} = \frac{10+0.5\cdot 40}{1+0.1\cdot 1.3} = 18\%$$

Specific resistance to loosening

$$F = k\rho_b{}^n W^m = 100\cdot 1{,}3^{1.5}\cdot 0{,}15^{\,0{,}8} \approx 204 \text{ kPa}$$

According to the calculation results: the optimum humidity for processing is 18%.; the soil is stable at shear stresses of up to 53.3 kPa; the recommended traction force for equipment is calculated based on a specific resistance of 204 kPa.

Simulation model of soil loosening

Simulation of a two-tier ripper in Comsol Multiphysics allowed us to obtain detailed data on the complex relationships between the mechanical properties of materials and external loads. Such modeling can be useful for optimizing the geometry of the working bodies of a two-tier ripper in engineering applications. However, when modeling, it is important to select a model of the process of interaction of the working parts of a two-tier ripper with the soil that most adequately describes the technological process and meets agrotechnical requirements. These results highlight the importance of detailed numerical analysis, which not only reveals key features of stress and strain distribution, but also suggests ways to optimize the design to improve its reliability and durability.
According to the design, the working parts (loosening paws) are used for non-moldboard surface tillage of the soil, i.e. loosening it to a depth of 16….30 cm and a width of 55….250 mm.
When calculating the work of a two-tier ripper, it is important to take into account the soil resistance and the reaction that occurs when the working element interacts with the soil. This includes calculations for the bending and strength of the working element, an assessment of the resistance force and the energy expended on loosening. To model a two-tier ripper, it will be necessary to develop a system of equations that describes the physical processes associated with the contact interaction of the soil and the working elements.

Statement of the problem

The equations of motion of the stress state of mechanisms for loosening the soil in a three-dimensional statement in the Cartesian coordinate system *Ox1x2x3,* under the action of a system of surface and volumetric forces have the form [17].

$$\sigma_{ij} + X_i - \rho\ddot{U}_i = 0,$$

defining relations between the stress tensor σ_{ij} and deformations ε_{ij}

$$\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl}$$

U_i and geometric Cauchy relations between ε_{ij} and the components of the displacement vector - U_i

$$\varepsilon_{ij} = \frac{1}{2}(U_{i,j} + U_{j,i} + U_{k,i}\,U_{k,j})$$

and boundary conditions

$$U_i\,|_{\Sigma} = U_i^{\Sigma}, \quad \sigma_{ij}n_j\,|_{\Sigma} = S_i$$

Where: X_i, S_i are volume and surface forces, U_i^{Σ} are specified on a part of the displacement boundary, n_j is the external normal, ρ is the density, C_{ijkl} (x)- are the elastic moduli, $i, j, k, l = 1, 2, 3$. For isotropic materials, the following relationships hold for the components of the elastic moduli tensor

$$C_{ijkl} = \lambda\,\delta_{ij}\delta_{kl} + \mu\,(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}),$$

where: $\lambda = \frac{E\nu}{(1-2\nu)(1+\nu)}$; $\mu = \frac{E}{2(1+\nu)}$ Lame coefficients, E is the elastic modulus, ν is Poisson's ratio.

In this problem, the volume forces - X_i are absent. The total soil resistance force for the stand with a tip is used as the surface force S_i, which is specified for a two-tier ripper and can be calculated using the following formula:

$S_1 = F_t$; $S_2 = F_w$; $S_3 = F_n$

Calculation scheme for the problem of soil loosening with a two-tier ripper on the Comsol application software package.

Soil contact interaction: modeled using contact conditions where soil resistance forces act on the posts and tips. Boundary conditions may include normal and tangential forces depending on the soil type and the angle of attack of the post. Resistance coefficients such as the angle of internal friction and cohesion can be used to model contact pressure. Figures 1 and 2 show the layout of the finite elements of the problem under consideration for loosening the soil with a two-tier ripper and its design. In the areas of impact of the tip on the soil, the number of finite elements increases, while the area of the element itself decreases. As a result, the degree of adequacy of mathematical modeling increases significantly.

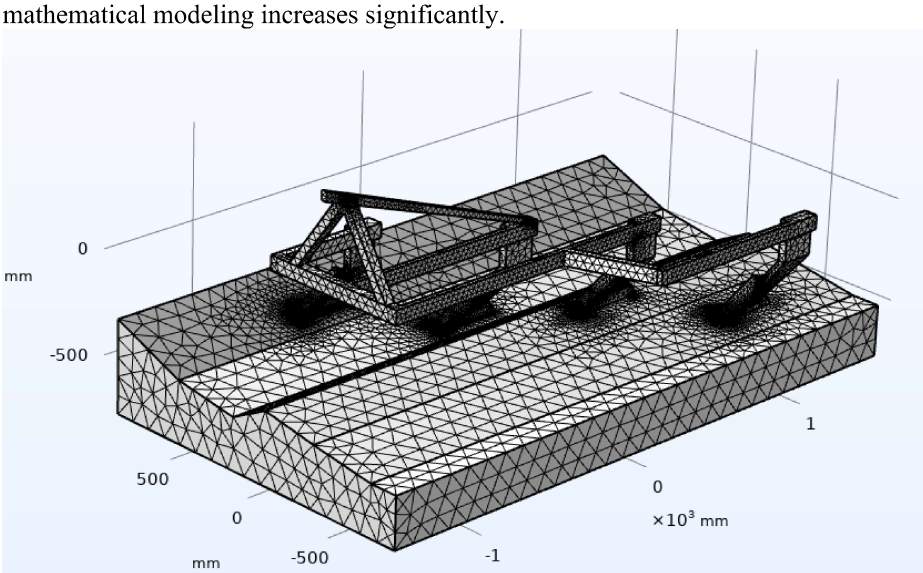


Fig. 1 Scheme of discretization of the composition "two-tier ripper-soil"

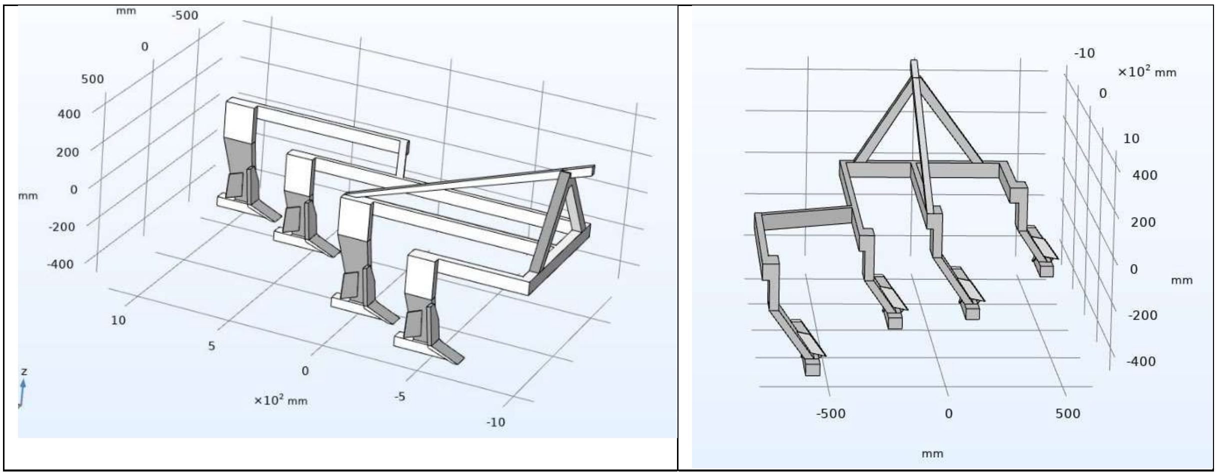
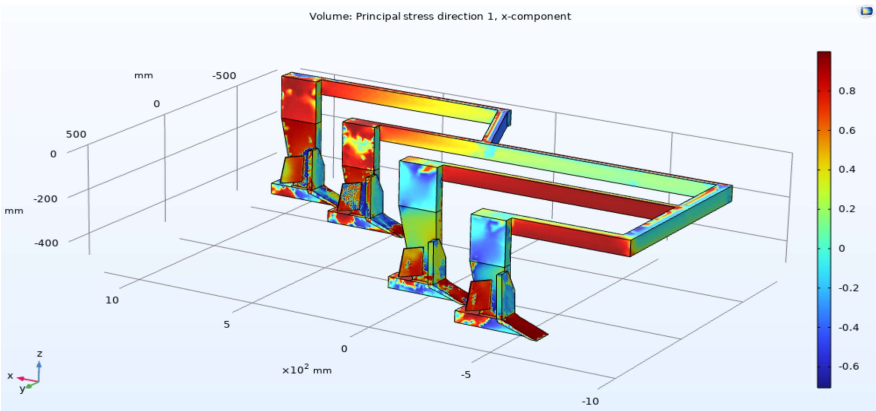


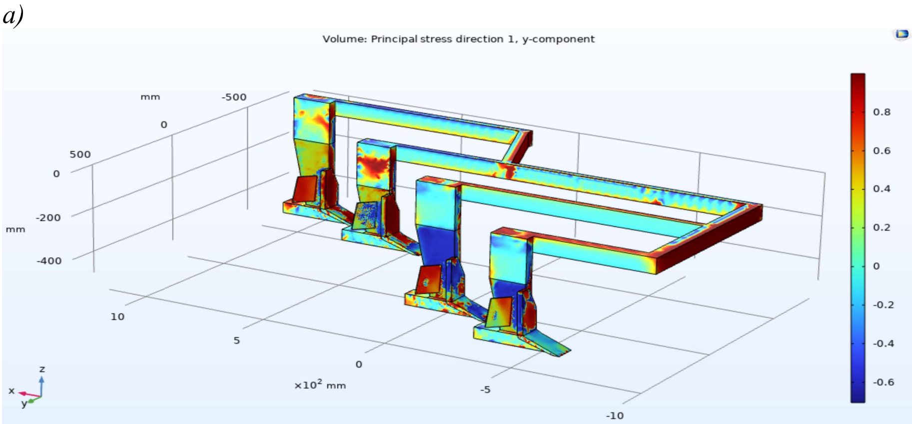
Fig. 2. Construction of a two-tier ripper

As the obtained results show, the highest values of the projection of the main stress $\vec{\sigma}_1$ in the direction *Ox* are observed on the *4*th post and *1,2,4* beams of the two-tier ripper (Fig. 3,*a*.). This fact can be explained by the fact that, according to the design feature, the tip *4* of the *4* th working element cuts deeper into the soil, as a result of which the highest stress concentration is achieved for $\vec{\sigma}_1$..

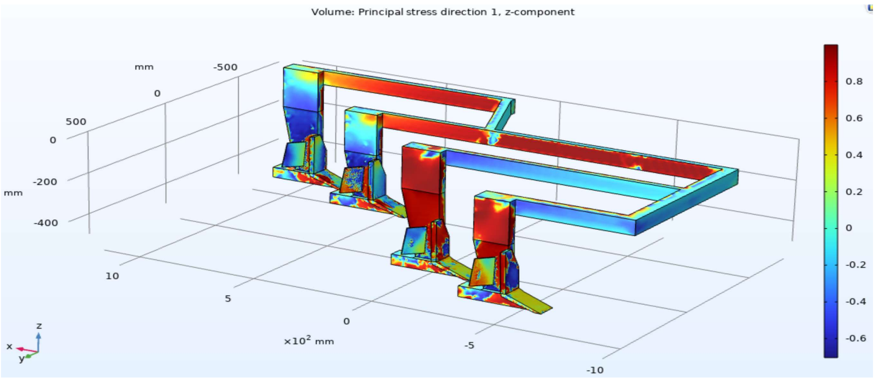
As expected, the concentration of the main stress -$\vec{\sigma}_1$. is not observed in the direction *Oy*, since the movement of the unit occurs in the *Oxz* plane (Fig. 3,*b*.). Due to the technological feature, the main share of the main stress $-\sigma_x$ is distributed to the first and second posts of the two-tier ripper. At the same time, the main share of the vertical pressure, without being transmitted to the *3*rd and *4*th post, is retained on the corresponding ridges of the two-tier ripper (Fig. 3,*c*.).



a)



b)



c)

Fig. 3. Distribution of isolines for the main stress vector $\vec{\sigma}_1$ along the coordinate axes for the two-tier ripper device; the first main stresses in the directions *Ox*, *Oy* and *Oz* ; *a*) - the main stress in the direction of the coordinate - *Ox*; *b*) - the main stress in the direction of the coordinate - *Oy*; *c*) - the main stress in the direction of the coordinate - *Oz*.

As follows from the obtained results, the largest values of the projection of the principal stress $\vec{\sigma}_2$ were observed in the *Oy* direction, and in the other directions they are negligibly small. It follows from Fig. 3 that on the beams of the two-tier ripper they were identical and evenly distributed. In the direction *Oy*, the distribution of isolines is almost identical in all posts. This fact is explained by the fact that the direction *Oy* is not a force direction for a two-tier ripper. Fig. 4 shows the graphs of the change in the deformation of the chisel *1,2,3,4* of the ripper working bodies.

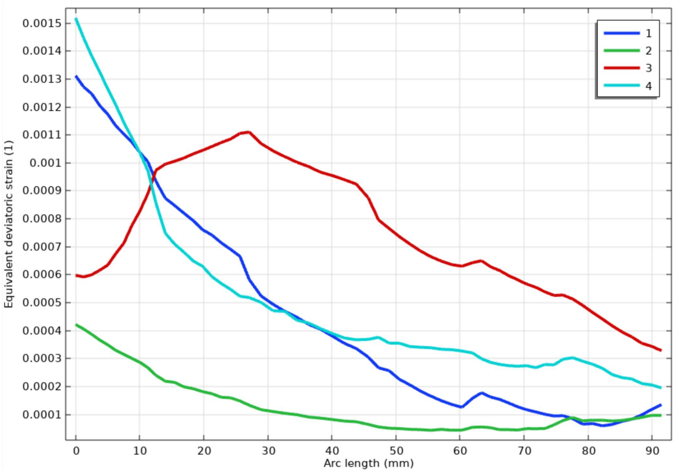


Fig. 4. Change in the deformation of the chisel of the *1,2,3,4* working bodies of a two-tier ripper at the initial stage of loosening.

As the process of loosening the soil with the chisel blade of the two-tier ripper continued, an oscillatory nature of the change in deformation was observed with clearly expressed resonance phenomena for all posts. At different distances of occurrence of resonance phenomena in all posts, significant deepening of the working parts' tips into the soil occurs. This was especially noticeable for the *4*th post, which pulls down the other posts. This fact should be taken into account when assessing the effectiveness of the structure as a whole.

Conclusion.

Thus, we have a simulation model of a tool for cultivating soil for agricultural crops. Using the developed models, it is possible to study various situations during soil cultivation with possible changes in the geometric profiles of the tools under consideration. Since the process considered in this problem is highly complex, the COMSOL package was used for its numerical solution. This software package is a powerful tool widely used by scientists and engineers around the world to model complex physical and engineering processes. One of the reasons for its popularity is the high accuracy of numerical results, which demonstrate good convergence with real experimental data. This makes COMSOL a reliable choice for solving problems that require taking into account many factors and complex relationships.

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