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DEVELOPMENT THE MATHEMATICAL MODEL OF THE PROCESS OF STRIPED SOIL TREATMENT BY THE METHOD OF DISCRETE ELEMENTS

The paper describes the general characteristics of the Strip-Till technology, its application and the design of Strip-Till cultivators, talks about the prospects of this technology, describes the advantages and disadvantages of the technology and highlights the ways of implementing the technology.

Each technology has its advantages and disadvantages and specifics of implementation - Strip-Till is no exception. In some farms, the technology is implemented quite easily and proves its effectiveness after harvesting and summing up, while in other farms it may be the opposite. One of the many reasons for this phenomenon is the design features of strip cultivators, which arise from the creative flight of the developer and the specific agro-climatic conditions for which these units are designed. The culture of work and agrarian business in a particular region also has a significant impact on some design features. For example, it is no secret that the school of mechanical engineering in Europe and the USA has many differences.

The article is devoted to the study of the interaction of the working bodies of Strip-Till units with the soil using the discrete element method. The paper considers modern aspects of the application of Strip-Till technology in the world and Ukraine, its advantages and disadvantages, and also analyzes methods for modeling physical processes of soil cultivation.

Considerable attention is paid to the development of a mathematical model of soil cultivation by the discrete element method using Hertz-Mindlin contact models, which take into account the adhesion and cohesion of particles. The article provides a calculation algorithm, the main physical and mechanical properties of soil particles, parameters for simulation, and also presents the modeling results.

The proposed model allows predicting the dynamics of the interaction of soil particles with working bodies, which will contribute to increasing the efficiency and optimizing the operation of Strip-Till units. The conclusions outline directions for further research to improve the methodology and practical application of the results obtained.

Key words: *discrete element method, Hertz-Mindlin model, Hertz-Mindlin theory, Poisson's ratio, Johnson-Kendall-Roberts theory, damping*

Introduction. Today, in addition to the United States, strip-till technology is used in some regions of Canada, as well as in Germany and other European countries. Ukraine was no exception, and domestic farmers are successfully working on strip tillage technology [1].

Also, this technology makes it possible to successfully carry out root fertilization of plants with the use of both natural and organic fertilizers when using appropriate equipment. The advantages of this technology are the early spring warming of strips of cultivated soil, the strip application of fertilizers to the root zone of plant growth, the reduction of soil compaction, insignificant fuel consumption, the disadvantages are the increase in the number of mice in the fields, significant initial costs for the purchase of equipment, the pesticide load on the soil, the necessary increased accuracy of driving units [2].

In Ukraine, in recent years, especially after the dry year of 2020, the Strip-Till technology is also gaining more and more practical implementation and demonstrating its effectiveness.

Interesting fact: American farmer David Hula (David Hula) in 2017, using Strip-Till technology and irrigation, achieved an incredible corn yield of 33.4 t/ha. And he won the National Corn Yield Contest. And in two years, he renewed his own record, growing 38.63 t/ha.

Analysis of recent research and publications. The analysis of the conducted studies of various calculation methods showed that the finite element method (FEM) can be used for the calculation of cohesive soils, which will make it possible to obtain both strength characteristics and information about the destruction and displacement of the soil layer. The method of computational hydrodynamics can be effective only for studying the characteristics of overmoistened soils, which significantly limits the range of soils studied. The most universal and reliable is the method of discrete elements, which makes it possible to reliably estimate such parameters as the power and qualitative characteristics of the soil cultivation process (the nature of the mixing of soil layers, the shape of the transverse profile, the degree of loosening of the soil) [3].

The purpose and objectives of the research. The purpose of this work is to develop a mathematical model of the process of soil cultivation using the method of discrete elements. The next task of the work is the development of a scheme of the stand for the implementation of the proposed model of experimental research.

Research materials and methods:

Consider the process of soil cultivation based on methods of modeling the behavior of loose materials, in particular based on the method of discrete elements, which is a balance of the mechanical movement of a particle of loose material.

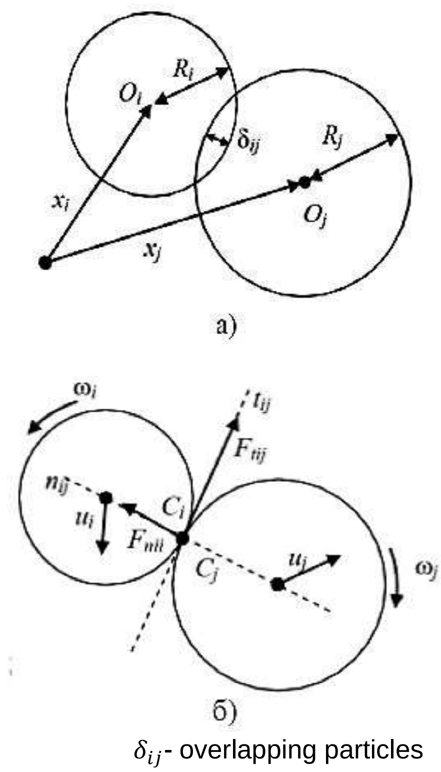
$$\begin{cases} m_i \dfrac{dv_i}{dt} = m_i b + \sum F_n, \\ I_i \dfrac{d\omega_i}{dt} = \sum (T_c + M_r), \end{cases}$$

where m_i - mass of the *i-th* particle; v_i - velocity vector of the center mass; ω_i - angular elocity vector; b - mass force vector; I_i - moment of inertia; F_n - a force acting on a particle through contact with another particle; T_c - the external torque that occurs when the particles come into contact; M_r - rolling resistance moment.

Soil modeling by the method of discrete elements is, first of all, the interaction of specific particles with each other, during which the deformation of the particles should occur. The interaction of these particles occurs with the help of contact models. The contact model defines the normal and tangential components of the force acting on the particles that collide. Often used are linear and nonlinear Hertz models [4].

The method of discrete elements, based on the fundamental laws of mechanics, eliminates the shortcomings of models of continuous (continuous) media.

The discrete material is formed from individual N elastic particles of spherical shape with radius R_i (Figure 1.a). The movement of each i-th element (particle) is determined by the coordinates of its center of gravity x_i and the angle of rotation θ_i around the center of gravity as a whole element (i=1, ..., N).



δ_{ij}- overlapping particles

Fig. 1. Contact interaction of discrete particles: model geometry (a); forces acting on contact (b).

The system of equations of motion for each particle in a rectangular Cartesian coordinate system will be written as follows:

$$m_i \frac{d^2 x_i}{dt^2} = F_i, \quad (2)$$

$$I_i \frac{d^2 \theta_i}{dt^2} = M_i (i = 1, \dots, N), \quad (3)$$

where t - time, m_i - mass of the particle, I_i - moment of inertia.

Vectors F_i are defined as the sum of the forces acting on the contacts of the *i-th* and *j-th* particles (including the force of gravity):

$$F_i = \sum_{i=1,i\neq j}^{N} F_{ij} + m_i g, \qquad (4)$$

Vector M_i arises as a moment of forces F_{ij} relative to the center of the *i-th* particle:

$$M_i = \sum_{i=1,i\neq j}^{N} M_{ij} = \sum_{i=1,i\neq j}^{N} (x_i - x_j) F_{ij}$$

Surface forces F_{ij} consist of frictional forces $F_{t,ij}$ and repulsion $F_{n,ij}$. The force of repulsion arises between particles under the condition of contact between the elements (δ_{ij} > 0) (Figure 1.a) and directed along the normal n_{ij} to the center of the ith particle (Figure 1.b). To determine it, we use the viscoelastic collision model:

$$F_{n,ij} = F^e_{n,ij} + F^v_{n,ij}, \qquad (6)$$

where $F^e_{n,ij}$ - elastic component; $F^v_{n,ij}$- viscous component.

According to J. Hertz, the elastic part of the force $F_{n,ij}$ is equal to:

$$F^e_{n,ij} = \frac{4}{3}\frac{E_i E_j}{3(1-v_i^2)E_j + (1-v_i^2)E_i}\sqrt{\frac{R_i R_j}{R_i + R_j}}\,\delta_{ij}^{\frac{3}{2}}, \qquad (7)$$

where v_i - Poisson's ratio, E_i - modulus of elasticity of the particle.

In the case of collision of a particle and a rectilinear boundary, in formula (7) it is sufficient to assume that one of the radii is equal to infinity.

The viscous component of the repulsive force is determined from the ratio:

$$F^v_{n,ij} = \gamma_n M_{ij} u_{n,ij}, \qquad (8)$$

where M_{ij} - the mass of the particles is given, $u_{n,ij}$ - projection of the relative speed of the collision point onto the axis n_{ij}, γ_n - the damping factor, which has the main effect on the speed recovery factor after impact.

The force of friction $F_{t,ij}$ is directed against the movement of the *i-th* particle relative to the *j-th*, and its value is determined by the ratio:

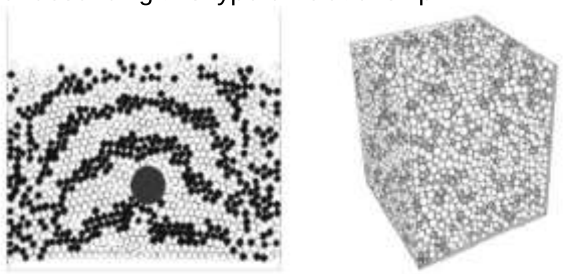
$$F_{t,ij} = -\sin(u_{t,ij})\, F_{t,ij} tg\varphi_t, \qquad (9)$$

where $u_{t,ij}$ - contact point velocity projection C_i relative to the speed of the point C_j on the axis t_{ij}, φ_t - angle of contact friction between particles.

Thus, the system of differential equations of the second order is relatively unknown x_i, θ_i and relations completely determine the motion and collision of a set of elastic particles simulating a discrete environment.

The method of discrete elements is implemented both on a plane (Figure 2 a) and in a three-dimensional coordinate system (Figure 2 b) [4].

Soil modeling assumes that particles undergo deformation during contact with each other. The Hertz-Mindlin model [6] is most suitable for describing this type of relationship.



a) b)

Fig. 2. Implementation of the method of discrete elements on the plane (a) and in the three-dimensional coordinate system (b)

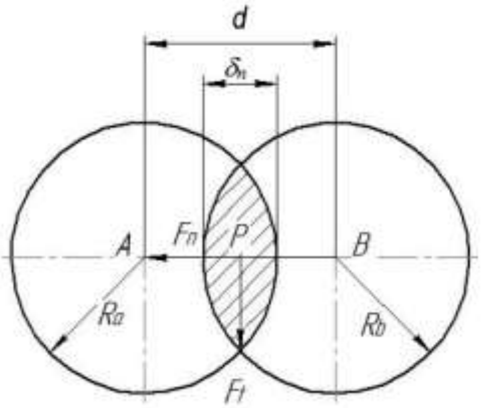
This model is non-linear and has a number of advantages: in case of exceeding the specified limit of the tangential force in the contact area, sliding occurs, and as soon as the value of the tangential force returns to the specified limit, there is no sliding in the contact area.

In this model, it is assumed that during contact, the particles will shift and overlap each other by a given amount, thus simulating the deformation of the medium (Figure 3).

This method of particle interaction can also be called the "soft sphere model" [6].

In the soft sphere model, the modeling process includes the following stages:

- setting the properties of particles and equipment in the computing area;
- inserting particles into the computing area by determining the position and speed;
- detection of particle-particle and geometry-particle contacts;
- - calculation of the force acting on each particle, using the appropriate contact model;
- determination of particle acceleration using Newton's second law, which is integrated over time to determine new particle states such as position and velocity. This process is repeated to track the particle dynamics over a long period of time until the desired result is obtained.



F_n , F_t - normal contact force and tangential contact force; A, B: centers of particles 1 i 2; R_a, R_b - radii of the particle 1 i 2; d - the distance between the centers of the particles C_1 i C_2; δ_n - overlap zone between particles 1 i 2; P - the central point of overlap.

Fig. 3. Model of contact between particles

After analyzing the available contact models of discrete elements, we came to the conclusion that the Hertz-Mindlin contact models are the most suitable for modeling the soil environment as a viscous-elastic-plastic loose body.

The Hertz-Mindlin contact model has several varieties:

1. Model and theory of Hertz-Mindlin sliding contact (without slipping);
2. Hertz-Mindlin model with adhesion of binding particles;
3. Hertz-Mindlin cohesive contact model with JKR (Johnson-Kendall-Roberts).

The Hertz-Mindlin sliding contact model and theory (no slip) is a simulation model of the MDE with a normal force based on the Hertz contact theory and a tangential force based on the Mindlin-Deresiewicz work. The contact between granular cells is modeled by a spring-damping system. The spring is the elasticity of the device. Damping is the weakening of the force or the object of dissipating the energy of motion. The damping represents the inelasticity, and the sliding block with the coefficient of friction represents the friction between the elements. The contact model between particle elements is shown in Figure 3.

According to Hertz's contact theory [6], the normal force F_n between particles is equal to (Figure 3)

$$F_n = \frac{4}{3} E^* \sqrt{R^*} \delta_n^{3/2},$$
$$\frac{1}{E^*} = \frac{1 - v_a^2}{E_a} + \frac{1 - v_b^2}{E_b},$$
$$\frac{1}{R^*} = \frac{1}{R_a} + \frac{1}{R_b}, \qquad (10)$$

where E^* - equivalent Young's modulus; R^* - equivalent radius; δ_n - normal overlap; E_a, v_a, R_a i E_b, v_b i R_b - Young's modulus; Poisson's ratio; and the radius of the contact spheres, respectively.

Tangential force F_t between particles is determined

$$F_t = -S_t \delta_t,$$
$$S_t = 8G^* \sqrt{R^*} \delta_n,$$
$$d = \left(\sum_i (\chi_{B,i} - \chi_{A,i})(\chi_{B,i} - \chi_{A,i}) \right)^{\frac{1}{2}}$$
$$(i = 1,2), \qquad (11)$$

where F_t - shear stiffness; S_t - tangential overlap; G* - equivalent shear modulus; $\chi_{A,i}$ i $\chi_{B,i}$ - coordinates of the centers A and B of the particle units, respectively; d - the distance between the centers of two particles.

The contact stiffness between two particles is modeled as a set of elastic springs with a constant rate and shear stiffness at the contact point (Figure 4). When two particles overlap, there is a normal and a shearing contact force at the point of contact that causes relative motion between the two balls at each step of the calculation. A parallel bond replaces the bond between soil clods.

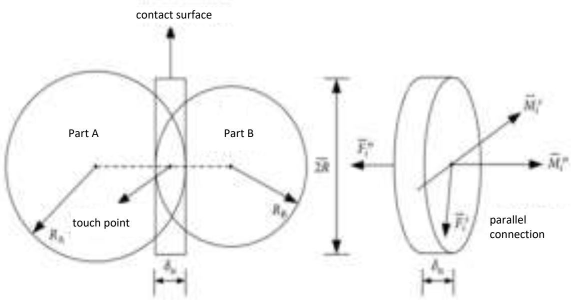


Fig. 4. Parallel connection on the contact surface between two particles

The normal overlap of two contacting particles is calculated as

$$\delta_n = R_A + R_B - d, \qquad (12)$$

where R_A i R_B - radii of particles A and B.

Stiffness coefficient of two particles in contact

$$k_n = 2E^* \sqrt{R^*} \delta_n,$$
$$k_s = \left(\frac{1}{2} - \frac{1}{3} \right) k_n, \qquad (13)$$

where k_n - coefficient of normal stiffness, k_s - coefficient of tangential stiffness.

The Hertz-Mindlin model with adhesion of binding particles. In this model, the adhesion between particles is taken into account - adhesion, which is taken into account by the additional Hertz-Mindlin force. This model is particularly suitable for simulating the interaction of the working bodies of tillage machines with the soil (Figure 5).

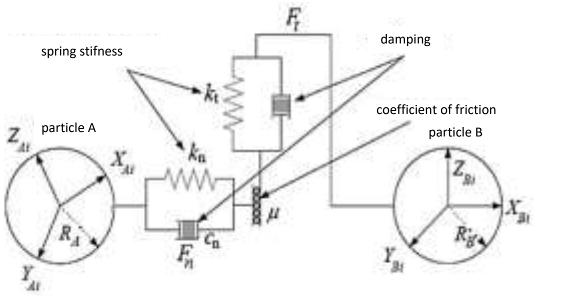


Fig. 5. Calculation scheme of the Hertz-Mindlin contact model

The interactions between the particles are calculated using the Hertz-Mindlin contact model using MDE software before the particles come together during bond formation. After the bond is formed, the force (F_nt) or torque (T_nt) on the particle is set to 0 and calculated using the following formulas:

$$\delta F_n = -v_n S_n A \psi_t, \tag{14}$$
$$F_t = -v_t S_t A \psi_t, \tag{15}$$
$$\delta T_n = -\omega_n S_t J \psi_t, \tag{16}$$
$$T_t = -\omega_t S_t \frac{1}{2} \psi_t, \tag{17}$$

where $A = 3{,}14R_B^2$; $J = (1/2)3{,}14R_B^4$; R_B - gluing radius; S_n i S_t - normal stiffness and tangential stiffness respectively; f_t - time step; v_n and v_t - normal velocity and tangential velocity of the particle, respectively; ω_n i ω_t - normal angular velocity and tangential angular velocity of the particle, respectively.

The connection between the particles is broken when the normal and tangential stresses exceed the specified values:

$$\sigma_{max} < \frac{-F_n}{A} + \frac{2M_t}{J} R_B,$$
$$\tau_{max} < \frac{-F_t}{F} + \frac{M_n}{J} R_B \tag{18}$$

Hertz-Mindlin cohesive contact model JKR (Johnson-Kendall-Roberts) takes into account the effect of van der Waals forces in the contact area and enables the user to model strongly adhesive systems such as dry or wet materials. In this model, the implementation of the normal elastic contact force is based on the Johnson-Kendall-Roberts theory presented in (Johnson, Kendal and Roberts 1971).

The Hertz-Mindlin cohesive contact model with JKR uses the same calculations as the Hertz-Mindlin (no-slip) contact model for the following types of forces:

- tangential force of elasticity;
- normal scattering power;
- tangential scattering force.

The normal force in the JKR model depends on t

$$F_{JKR} = -4\sqrt{3{,}14\gamma E^*} a^{\frac{3}{2}} + \frac{4E^*}{3R^*} a^3,$$
$$\delta = \frac{a^2}{R^*} - \sqrt{4\pi\gamma a / E^*}, \tag{19}$$

This model provides gravitational coupling forces even when the particles are not in physical contact. The maximum gap between particles with a non-zero force is determined by the expression

$$\delta_c = -\sqrt{4\pi\gamma a_c / E^* + \frac{a_c^2}{R^*}}, \tag{20}$$

$$a_c = \left[\frac{9\pi\gamma R^2}{2E^*}\left(\frac{3}{4} - \frac{1}{\sqrt{2}}\right)\right]^{\frac{1}{3}} \tag{21}$$

When $\delta < \delta_c$ the model returns zero force. The maximum value of the adhesion force occurs when the particles are not in physical contact, and the distribution gap is smaller than δ_c. The value of the maximum adhesion force, called the separation force, is determined by the expression

$$F_p = -\frac{3}{2}\pi\gamma R^*, \tag{22}$$

The friction force calculation differs from the Hertz-Mindlin (no-slip) contact model in that it depends on the positive repulsive part of the normal force F_{JKR}. As a result, the Hertz-Mindlin JKR cohesive contact model provides a higher friction force when the cohesive component of the contact force is higher.

Although this model was originally developed for small dry particles, it can be used to model wet particles such as soil. The force required to separate two particles depends on the surface tension of the liquid and the contact angle θ.

$$F_p = 2\pi\gamma_s \cos(\theta) \sqrt{R_i} R_j, \tag{23}$$

As contact models, we will choose the Hertz-Mindlin models with adhesion of binding particles and the Hertz-Mindlin cohesive contact model. To develop a model of the soil environment using the method of discrete elements, it is necessary to determine its main parameters and carry out calibration of the properties of soil particles.

The MDE parameters required for simulation can be divided into two groups, namely: material properties and interactions. Material properties are defined, for example, as internal particle characteristics: shape, size distribution, density, Poisson's ratio, and shear modulus. Interaction properties are characteristics that a particle exhibits in relation to its contact with boundaries, surfaces, and other particles. The coefficient of recovery, coefficient of rolling friction and coefficient of static friction are the most important properties of interaction [6].

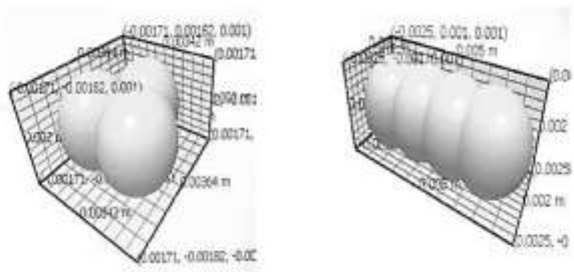
During discrete element soil modeling, soil particles can be simulated by combining different combinations of spherical objects. The complex shape of soil clods is modeled by overlapping spherical objects at different distances, building them in a chain, creating triangular objects, etc. [6].

We used the following combinations of spherical particles: a sphere, three spheres on the vertices of an isosceles triangle, four spheres lined up in a chain (Figure 6), the diameter of the sphere is assumed to be 1 mm.

On the basis of literary sources and own research, the physical and mechanical properties of soils were determined and the following parameters were established:

- Poisson's ratio ν = 0,2...0,35;
- coefficient of static friction f = 0,35...0,45;
- shear modulus G = 10...12 МПа;
- Young's modulus E = 30...35МПа;
- particle density $p_п$ = 2600 кг/м3.

As initial conditions, it is necessary to set the speed of movement of the geometry in the calculation area of the program. We have adopted such a range of operating speeds 0,5...2,5 m/s.



a) b)

a - 3 spheres on the vertices of an isosceles triangle; b - 4 spheres in a row

Fig. 6. Models of soil particles

The physical models of the computational algorithm involve the tasks of three types of models: models of interaction of particles with particles; models of interaction of particles with geometry and models of assignment of forces acting on particles.

Particle-particle and particle-boundary conditions:

- the stiffness coefficient was set equal to 0.8 (defined as the ratio of tangential stiffness to the normal stiffness of the load and used when calculating the tangential force during contact);
- the coefficient of static friction between particles and the coefficient of static friction between the boundary and particles were set equal to 0.5;
- the coefficient of dynamic friction between particles and the coefficient of dynamic friction between the boundary and particles were set equal to 0.5;
- the rolling resistance coefficient was set equal to 0.9;
- gravitational component: X = 0, Y = 0, Z = - 9.81 m/s2;
- time step Δt = 0.00015 s, total calculation time 10 s.

After setting the simulation conditions, the calculation is performed according to the algorithm presented in the diagram (Figure 7).

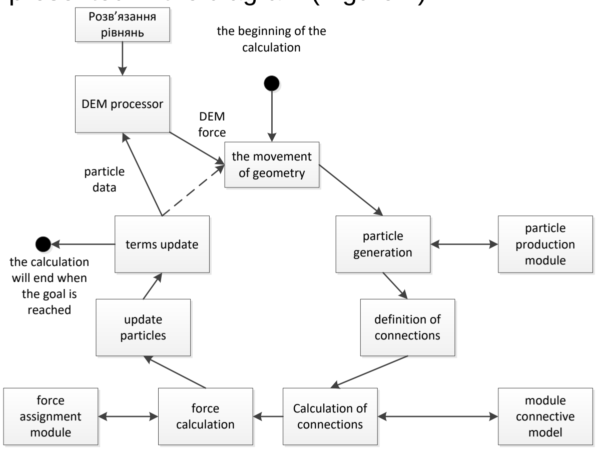


Fig. 7. Implementation scheme of the particle interaction model

As initial parameters, we get the average values of the normal and tangential component forces acting on the elements of the geometry that are included in the calculation area. The resulting force values are equivalent to the tool's traction resistance.

The contact model is implemented in the blocks "Definition of connections", "Calculation of connections", "Connection model module".

The given algorithm is a closed, cyclical mechanism for the implementation of built-in mathematical models, which gradually leads to the set goal in the process of iterations.

Conclusions and directions for further research. To develop a model of the process of interaction of the working bodies of the strip-till unit with the soil, the method of discrete elements was adopted as the basis. It was established that the Hertz-Mindlin contact models, taking into account adhesion and cohesion, are the most suitable models for describing the type of connections between soil particles.

The main physical and mechanical properties of soil particles for modeling by the discrete element method have been established: Poisson's ratio ν = 0,2...0,35, coefficient of static friction f = 0,35...0,45, shear modulus G = 10...12 MPa, Young's modulus E = 30...35MPa, particle density $p_п$ = 2600 kg/m^3.

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РОЗРОБКА МАТЕМАТИЧНОЇ МОДЕЛІ ПРОЦЕСУ СМУГОВОГО ОБРОБКУ ҐРУНТУ МЕТОДОМ ДИСКРЕТНИХ ЕЛЕМЕНТІВ

У роботі описана загальна характеристик технології Strip-Till, її застосування та конструкцію культиваторів Strip-Till, розповідають про перспективи цієї технології, описують переваги та недоліки технології та висвітлюють шляхи реалізації технології.

Кожна технологія має свої переваги та недоліки та специфіку впровадження – Strip-Till не є винятком. В одних господарствах технологія реалізується досить легко і доводить свою ефективність після збирання врожаю та підбиття підсумків, а в інших господарствах може бути навпаки. Однією з багатьох причин цього явища є конструктивні особливості смугових культиваторів, які випливають із творчого польоту розробника та специфічних агрокліматичних умов, для яких ці агрегати розраховані. Культура праці та аграрного бізнесу в тому чи іншому регіоні також має істотний вплив на деякі особливості конструкції. Наприклад, ні для кого не секрет, що школа машинобудування в Європі та США має багато відмінностей.

Стаття присвячена дослідженню взаємодії робочих органів агрегатів Strip-Till із ґрунтом за допомогою методу дискретних елементів. У роботі розглядаються сучасні аспекти застосування Strip-Till технології у світі та Україні, її переваги та недоліки, а також аналізуються методи моделювання фізичних процесів обробітку ґрунту.

Значну увагу приділено розробці математичної моделі обробітку ґрунту методом дискретних елементів з використанням контактних моделей Герца-Міндліна, які враховують адгезію та когезію *частинок. У статті наведено алгоритм обчислення, основні фізико-механічні властивості ґрунтових частинок, параметри для симуляції, а також представлені результати моделювання.*

Запропонована модель дозволяє прогнозувати динаміку взаємодії частинок ґрунту із робочими органами, що сприятиме підвищенню ефективності та оптимізації роботи Strip-Till агрегатів. У висновках окреслено напрями подальших досліджень для удосконалення методології та практичного застосування отриманих результатів.

***Ключові слова**: метод дискретних елементів, модель Герца-Міндліна, теорія Герца-Міндліна, коефіцієнт Пуассона, теорія Джонсона-Кендалла-Робертса, демпфування/*

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