Review of numerical methods for modeling the interaction of soil environments with the tools of soil tillage machines

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Abstract: A classification is given of methods for studying the process of interaction of soil environments with the tillage tools of soil-cultivating machines. The methods are divided into two groups: mathematical modeling and experimental research. Mathematical methods for studying soil interactions using numerical modeling methods that allow one to overcome the shortcomings of analytical and empirical approaches are considered in more detail. A classification, existing software, and an analysis of the possibilities of continuous and discrete numerical methods are given. Studies were performed using continual methods are analyzed: finite element method (FEM) and computational fluid dynamics (CFD). Also studies using discrete methods are considered: the discrete element method (DEM) and the smooth particle hydrodynamics (SPH). An analysis of existing studies has shown that the finite element method can be used for cohesive soils, making it possible to obtain both strength characteristics and data on the process of destruction and displacement of the soil massif. The computational hydrodynamics method can be effectively applied only to the study of the power characteristics of overmoistened soils. Attempts to extend this approach to a wider range of soils lead to significant errors. Discrete methods are most versatile and reliable. So the method of discrete elements allows to reliably assess both the power and quality characteristics of the tillage process. For example, the shape of the transverse profile, the degree of loosening (compaction) of the soil, the nature of mixing of the soil layers.

1. Introduction
At the moment there are several methods for studying the process of interaction of soil environments with the tillage tools of various machines.

They can be divided into two large groups, this is mathematical modeling and experimental studies (figure 1). Mathematical methods are divided into classical soil mechanics and numerical methods. Experimental studies can also separate scalable tests and full-scale.
Figure 1. Methods for studying the interaction of soil and tillage tools.

2. Material and methods

2.1. Investigation of the interaction of soil and tillage tools with the methods of classical soil mechanics
Mathematical methods of classical soil mechanics are understood as approaches aimed at finding an analytical solution (classical soil mechanics). Currently, there is no consensus on the interaction and movement of soil caused by tillage tools. This question is relevant despite the significant amount of work devoted to the study of soil treatment. Different results are due to those soil models used by the authors [1-3].

So, G.N. Sineokov considers a model that likens the soil to a rigid elastic body [4]. L.V. Gyachev considers two soil models: undeformable, like an absolutely rigid body, and deformable, in which the absolute displacements of particles coincide with the direction of action of forces. Using the relations of spherical trigonometry, L.V. Gyachev derived an equation for the motion of a soil layer along a wedge for a compressible layer [5].

The most common scheme of the interaction of the wedge with the soil at the present time is the scheme of the process of formation deformation by the dihedral wedge, proposed by V.P. Goryachkin [3, 6], Panov and Sineokov [4].

2.2. The study of the interaction of soil and experimental studies by numerical methods
The development of computational capabilities of computer equipment and computer-aided design systems made it possible to reliably reproduce the three-dimensional geometry of tillage tools. This opened up opportunities for eliminating the shortcomings of analytical and empirical methods for studying soil interactions through the use of numerical simulation methods [7].

Two types of numerical methods, continuous and discrete approaches, are used to model the interaction with the soil. Continuous methods include the finite element method (FEM), which consists in the division into a finite number of subdomains (elements) the region in which the solution of differential equations is sought. There are also two large groups of research. The first includes studies in which mathematical models and solvers are created directly by the authors of the project. The resulting software products are distinguished by a narrow specialization and a complex uninformative user interface that actually limits the circle of their potential users to its authors.

Another group of intensively developing research is the use of ready-made programs for the implementation of calculations by the finite element method. They have a wide functionality and
friendly user interface. Allow to investigate the volume models exported from CAD. The most famous programs for calculations using the finite element method are ANSYS, NASTRAN, ABAQUS, LS-DYNA, COSMOS/M.

Computational fluid dynamics (CFD) are also among the continual models for studying soil interactions. This is a subsection of continuum mechanics, including a set of physical, mathematical, and numerical methods designed to compute the characteristics of flow processes. The use of continuous numerical methods does not always give a reliable result, due to the assumption of continuity of the soil. This introduces significant errors, since in the process of processing the destruction of the soil mass and the movement of the formed aggregates.

Figure 2. Numerical methods used for modeling soil-tillage tool interactions.

Most effectively eliminates the shortcomings of continuous numerical methods, the discrete element method (DEM). This is the most suitable method for modeling soil treatment processes, since it can describe soil destruction, deformation and displacement of soil aggregates. The particle dynamics method has similar capabilities with the discrete element method. One of its well-developed variants is the molecular dynamics method. It consists in representing the environment as a set of interacting particles – material points or solid bodies. The most famous programs for calculations using the molecular dynamics method are AMBER, CHARMM, GROMACS, GROMOS, NAMD.

To draw a clear boundary between the method of particle dynamics and the method of discrete elements is difficult. The main difference is that the first was developed as a generalization of the molecular dynamics method, and the second as a generalization of the finite element method. Currently, both methods can lead to almost identical computational algorithms. The name of the method is actually determined by which software packages are used for the calculation. The most well-known programs implementing the discrete element method are, PFC2D and PFC3D, EDEM, Chute Maven, GROMOS.
96, ELFEN, MIMES, PASSAGE® / DEM.

Also recently, studies have appeared on the modeling of soil environment using the method of smooth particle hydrodynamics (SPH). The SPH method divides the environment into discrete elements called particles.

3. Results and discussion

Let us consider in more detail the research on the interaction of the soil environment and tillage tool, performed using various methods.

3.1. Research using the finite element method (FEM)

The study [8] provides data on the modeling of the interaction of a dihedral wedge and a plowshare plow with the soil. The LS-DYNA program was used (figure 3). To describe the behavior of the soil, the Drucker-Prager model (type 193) was chosen. Soil parameters: density of 1400 kg/m³; modulus of elasticity 17 MPa; Poisson's ratio 0.25; friction angle 25°; dilatancy angle of 38°.

Created computer models of interaction adequately describe the real processes of tillage. They can be used to disclose the general laws of stress distribution and deformations in the interaction of tillage tools with soils. However, the study of such important power indicators as traction resistance, degree of loosening, etc., was not conducted in this work.

![Figure 3. Chipping of the soil layer with a wedge (a) and the turnover of the soil layer by the plowing surface (b).](image)

In the study [9], the finite element method (FEM) was used to simulate the process of cutting soil by a plow using the Abaqus program (figure 4). To imitate the soil, the elastoplastic model of Mohr-Coulomb was used. Soil parameters: density 2000 kg/m³, Young's modulus 4.106 N/mm², Poisson's ratio 0.3, plastic deformation 160 N/mm². The plow surface created in the SolidWorks software was imported into Abaqus as a discrete solid with a reference point at the tip of the blade. At this point, the reaction force with its three orthogonal components was calculated. The influence of the cutting angle (the angle between the horizontal generatrix and the direction of motion) and the lift angle (the angle between the surface of the blade and the horizontal line in perpendicular cross section to the cutting edge) on the traction resistance was investigated.

As a result of the virtual experiment, three components of traction resistance were obtained. According to the authors, the results are in good agreement with other studies. However, as can be seen from the cited figures, the shape of the transverse soil profile formed is weakly consistent with that obtained in reality.
3.2 Studies using computational fluid dynamics (CFD)

In studies [10], the method of computational fluid dynamics (CFD) was used. The ANSYS CFX program was used to simulate the interaction of the sweep tillage tool with the soil environment (figure 5). The plastic model of Bingham (Bingham plastic) was used. According to the simulation results, the pressure was controlled at several points, and the depth and width of the sweep tillage tool were also varied. In addition, traction resistance and vertical force were recorded. Soil properties were modified by the authors by random selection. It was necessary to obtain the forces correlated with the experimental data. This fact indicates that the properties of real cohesive soils are difficult to reliably describe the plastic soil of Bingham.

For traction resistance forces, modeling correctly predicted an increase in force with an increase in the width of the grip in seven cases out of eight. Five experiments with different conditions had an error of less than 100%. One experiment had an error exceeding 200%. The simulation incorrectly predicted which the sweep tillage tool had a higher vertical force in three experiments. There were only two experiments with an error of less than 100%. Three experiments had errors that exceeded 200%.

Figure 5. Modeling the interaction with the soil of the sweep tillage tools using the CFD method.

In studies [11], the computational fluid dynamics (CFD) method was also used. The interaction of the sweep cultivating tool with the soil environment was modeled using the FLUENT 6.3 program (figure 6). In modeling, it was assumed that the soil behaves like Bingham's visco-plastic material. The modeling was carried out for three types of sweep tillage tools having the same geometric shape, but with different angles between the cutting edges.

It was found that the distribution of pressure over the surface of the sweep tool depends on the position of the cutting surfaces and the characteristics of the soil. Simulation shows that the maximum...
pressure is fixed on the cutting edges. However, the study remains unclear the question of the values of the longitudinal and vertical components of the vector of traction resistance.

**Figure 6.** Simulation of interaction with the soil of the sweep tillage tools using the CFD method.

### 3.3 Studies using the method of the dynamics of smoothed particles (SPH)

In the study [12], the interaction between the soil and tillage tools was modeled using the non-grid method of the dynamics of smoothed particles (SPH). The ANSYS AUTODYN program was used (figure 7). The description of soil interactions was carried out according to the modified Drucker-Prager model.

The results of traction resistance were compared with the obtained analytical method and with the actual tests in the soil bin. According to the authors, the results were 5-10% less accurate than when using DEM. It also took significantly less computational resources and time. Nevertheless, SPH always increases real strength, which requires the need for more thorough research and a more accurate material model.

**Figure 7.** Modeling the interaction of the tillage tools with the soil by the SPH method.

In a study [13], a virtual prototype of an inclined rotary tiller based on the SPH method was also investigated (figure 8). The description of soil interactions was carried out according to the simple soil and crushable foam model. The shape of the furrow was also determined by modeling. The correctness of computer simulation was confirmed by comparing the virtual experiment and real laboratory research. In all cases, the energy consumption in modeling above experimental data, but does not exceed 10%.
3.4 Studies using the discrete element method (DEM)
In the study [14], the displacements of the soil and the forces of traction resistance of soil-tillage tools were measured using the discrete element method DEM (figure 9). Sweep tillage tool had different processing widths: 153, 280 and 330mm. The simulation model was built using the PFC3D program.

The results of measuring traction resistance and vertical force showed insignificant discrepancies with experimental data and the absence of contradictions with classical soil mechanics. However, some differences were identified. For example, the traction resistance increased nonlinearly with an increase in the width of capture of the sweep tillage tools, and in some experiments the vertical force had the opposite direction (the push force was fixed). All these facts may indicate, on the one hand, the need to correct the parameters of the model, and on the other, the possibility of the method of revealing new patterns of interaction.

The second part of the study is devoted to the study of the displacement of soil particles and the shape of the formed soil profile. It was shown that the method of discrete elements is able to control the movement of individual particles under the action of external forces and simulate their large displacements. This makes DEM a promising tool for modeling soil interaction with tillage tools. However, there were significant discrepancies in soil displacements between the model and the test results. They may be due to incorrect viscous damping values in the model. The damping coefficients could dissipate too much of the energy of the particles and the contacts, which suppressed the movement of the particles, resulting in smaller displacements. Another possible reason may be that the contact model or model parameters were selected incorrectly. In the future, it is necessary to work out the calibration of communication parameters and the use of different contact models.
In a study [15], experimental data and results obtained using FEM simulations were verified using DEM simulations (figure 10). The model was created in the program EDEM.

![Figure 10](image)

**Figure 10.** Modeling the interaction of the tillage tool with the soil:
(a) – finite element method; (b) – laboratory tests; (c) – method of discrete elements.

A contact model of linear cohesion with an integrated hysteresis spring was used. To create a particle size distribution and minimize their number, up to 250000 particles were used. The smallest particle was 3 mm in diameter. A total of 221313 particles were generated. The use of this particle size distribution made it possible to accurately simulate the bulk density of the soil. Despite the fact that the crack propagation is clearly visible on the digitized images obtained during tests in a glass-walled soil bin, no cracks appeared in the DEM modeling. This can be explained by the fact that the particle sizes were larger than in the soil bin. Therefore, even if a crack was formed, it was invisible because crack size is smaller than DEM particles.

The results of the study showed that the best prediction of traction resistance and vertical force was obtained using DEM (figure 10). The differences with the experimental data are explained by the large particle size used in DEM modeling. According to the authors, in order to improve results, future work should focus on using more irregularly shaped soil particles.

4. Conclusions
Analysis of the research has shown that the finite element method (FEM) can be used for cohesive soils, allowing one to obtain both strength characteristics and data on the process of destruction and displacement of the soil massif. The computational hydrodynamics method (CFD) can be effectively applied only to the study of the power characteristics of overmoistened soils. Attempts to extend the data approach to a wider range of soils lead to significant errors. Discrete methods are most versatile and reliable. So the method of discrete elements (DEM) allows to reliably assess both the power and quality characteristics of the tillage process. For example, the shape of the transverse profile, the degree of loosening (compaction) of the soil, the nature of mixing of the soil layers.

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