Machinery & Energetics
Vol. 14, No. 1. 2023

Journal homepage:
https://technicalscience.com.ua/en

UDC 631.31:519.67
DOI: 10.31548/machinery/1.2023.09

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Simulation of the interaction between the working bodies of tillage machines and the soil in Simcenter STAR-CCM+

Abstract. The lack of simple analytical physical and mathematical models complicates the investigation of the interaction of tillage working bodies with the soil when designing new structures. To simplify these calculations within the framework of agricultural machinery engineering, it is necessary to use software that integrates the development of agricultural mechanics. The purpose of this study was to model and investigate the interaction of tillage working bodies with the soil using Simcenter STAR-CCM+. For this, the volumetric fluid method and the discrete element method were used. When creating the model, the main physical and mechanical properties of the soil were used. As a result, the simulation of the interaction of the most common tillage working bodies, such as a tooth of a duck-foot cultivator, a disc harrow on an elastic stand, a subsoil cultivator (chisel plough), a mouldboard plough, and a smooth roller, was modelled using volume-of-fluid method and discrete element method. The application of the volume-of-fluid method helped establish a non-primary flow of the soil relative to the working body, while the discrete element method determined the distributions of velocities and forces of interaction of soil particles. It was found that both proposed methods can be useful for modelling the interaction of the tillage working body with the soil in Simcenter STAR-CCM+. Complementing each other, they create a general picture of the physics of the interaction of the tillage tool with the soil. Using Simcenter STAR-CCM+, the interaction process was visualized and the height of the formed ridges and furrow depths and their location in space were

Article's History: Received: 21.10.2022; Revised: 25.01.2023; Accepted: 22.02.2023.

Suggested Citation:
Kobets, A., Aliiev, E., Tesliuk, H., & Aliieva, O. (2023). Simulation of the interaction between the working bodies of tillage machines and the soil in Simcenter STAR-CCM+. *Machinery & Energetics,* 14(1), 9-23. doi: 10.31548/machinery/1.2023.09.

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determined. The application of the obtained models will enable the agricultural engineers to quickly develop innovative designs of tillage tools based on their interaction with the soil

Keywords: tools; numerical modelling; volumetric fluid method; discrete element method; velocity distribution; pressure

INTRODUCTION

To study the interaction of the working bodies of soil tillage machines with the soil, the latter should be formalized in the form of a physical and mathematical model of the environment in such a way that the properties of this model most fully correspond to the physical and mechanical properties of the real soil. A considerable number of studies investigate the interaction of tillage working bodies with the soil. Interaction models developed by V.P. Sysolin *et al.* (2001), Ya. Gukov (2007), O. Kozachenko *et al.* (2021a) and others deserve great attention. A.S. Kushnarev (2010) used the form of representation of the soil structure model and the types of deformations that occur during interaction as the basis of the classification of the interaction of tillage working bodies with the soil. As noted by V.P. Kovbasa (2006), V.F. Pashchenko & S.I. Kornienko (2016), this approach helped group the attempts made by many researchers to develop certain models of interaction of various working bodies according to certain characteristics. According to the form of presentation of the model of soil construction, all works related to the interaction of working bodies with the soil can be divided into four groups: solid body, continuous elastic medium, continuous incompressible fluid medium, continuous elastic-viscous-plastic medium.

Therewith, as an analytical apparatus, the following are used: methods of solid body mechanics, methods of the theory of elasticity and its simplified variants, methods of soil mechanics, methods of the theory of similarity and dimensions, methods of statistical mechanics (Hutsol & Kovbasa, 2016). Each of the presented studies is interesting in its approach to solving the technological problem of the interaction of the tillage working body with the soil environment. Thus, I.A. Shevchenko (2016) used the Mohr-Coulomb theory, which complements the theory of soil strength, in addition to the obtained equation of the movement of a material particle of soil on the surface of a tillage working body. Based on the results of experimental studies on the optimization of agrophysical properties of the arable horizon, I.A. Shevchenko (2016) considered the differentiated soil structure. M.V. Bakum & D.A. Yashchuk (2011) considered the issue of sketch geometry of determining the height of the ridges above the bottom of the furrow during tillage. O.P. Hutsol & V.P. Kovbasa (2016) presents the physical equations of the relationship between stresses and deformation rates for the soil environment when a soil-processing working body acts on it. Each of the presented models is used separately from each other, which leads to only a one-sided consideration of the scientific and technical difficulty of simulating the interaction of the working bodies of tillage machines with the soil.

J.B. Barr *et al.* (2019), K.A. Aikins *et al.* (2023), J. Zhang *et al.* (2023) stated that in the design and optimization of agricultural machinery, the discrete element method (DEM) has played a major role due to its ability to accelerate the design and production process due to the reduction of repeated prototyping, testing, and evaluation in experimental conditions. In the field of soil dynamics, DEM was mainly used in the design and optimization of soil tillage working bodies. This numerical method can capture the dynamic and volumetric behaviour of soils and soil-working body interactions (Xu *et al.*, 2022; Ucgul, 2023). The presented pool of information consolidates the available working approaches and helps identify model gaps that, if addressed, will advance the current soil dynamics modelling capability. The purpose was to simulate and investigate the interaction of tillage working bodies with the soil using the capabilities of Simcenter STAR-CCM+.

LITERATURE REVIEW

M. Ucgul *et al.* (2016) stated that modelling the soil-tool interaction is a complex process due to the variability of the soil profile, the nonlinear behaviour of the soil material, and the dynamic effects of soil flow. An approach that will provide further insight is the Discrete Element Method (DEM). In this study, topsoil subsidence during the soil-mouldboard interaction process was simulated using the DEM. A procedure was developed to compare and quantify the ground motion and subsidence of the surface layer of DEM simulations with soil channel and field results. The results of the study suggest that DEM has the potential to predict soil movement from tillage tools, including soil inversion and surface subsidence.

J. Zhang *et al.* (2023) built a model of the interaction of the rotary blade working body with the soil using the DEM. The modelling process reflects the blade-soil interaction law, and the accuracy of the simulation model is verified by field tests. The simulation model had good accuracy at all factor levels. The model built in this study can provide a theoretical framework and technical reference for the interaction mechanism of rotary tillage and soil, optimization of geometry, selection of working parameters.

A.A. Tagar *et al.* (2015) used the finite element method (FEM) to model soil failure patterns associated with consistency limits and soil sticking point, comparing the simulation results with soil failure patterns observed in a soil bunker and in the field. The results strongly suggested that the FEM is a useful tool for creating soil failure models, but the simulation models correlated better with the soil channel than with the field test results. It was concluded that the FEM can provide accurate modelling of soil failure structures under soil hopper test conditions, but the soil hopper results do not meet the satisfactory results of field studies.

A. Ibrahimi *et al.* (2015) illustrates the use of the FEM to model the interaction of a mouldboard plough. The Drucker-Prager elastoplastic model was used to model the behaviour of the sandy soil material. The mouldboard was considered as a discrete solid body with a reference point at the top, wherein three orthogonal components of forces (vertical, lateral, and sediment) were calculated. In this study, the influence of the blade cutting depth, work speed, cutting angle and elevation angle on soil tillage effort was investigated. It was concluded that the FEM can be used to understand the effects of mouldboard design and operating conditions on tillage forces, energy requirements and soil overturning quality. J.B. Barr *et al.* (2019) studied the interaction of plough shares using field experiments and modelling according to the DEM.

T. Okayasu *et al.* (2012) modelled the interaction of a tillage working body using a three-dimensional plough geometry and a soil layer modelled by the DEM particles. By introducing an element of bond between particles, the soil adhesion was arranged to simulate an actual cohesive soil. Soil cutting profiles were investigated in the context of variations in soil properties and tillage rates. Subsequent plough reaction forces were estimated from the simulation results. The simulated reaction forces were qualitatively consistent with the experimental data.

T. Xu *et al.* (2022) developed a precision seeding plant analysis model based on the DEM coupled with the MBD method (many body dynamics). The soil covering and compaction process was modelled and analysed. A comparison between the experimental results and the simulated results indicated that the trend was similar, and the two results were close. M. Ucgul (2023) modelled the interaction between the soil and a one-sided modified disc plough using the DEM. Since the disc plough is a passively driven tool, the rotating speed of the disc plough was modelled using the DEM-MBD combination. Our experience in numerical modelling of technological processes of agro-industrial production (Kozachenko *et al.*, 2021b; Aliyev *et al.*, 2022) allows us to assert the possibility of using the Simcenter STAR-CCM+ software package for simulating the interaction of the working bodies of tillage machines with the soil.

When designing new structures of tillage working bodies, agricultural engineers cannot investigate their interaction with the soil due to complex analytical physical and mathematical models developed by the above-mentioned renowned scientists and researchers. To simplify the calculations of this interaction within the framework of agricultural machine engineering, it is necessary to summarize the achievements of Ukrainian and foreign agricultural mechanics into a single software. Today, the use of numerical modelling of the interaction of the working bodies of soil tillage machines with the soil is already being practised in specialized software packages.

MATERIALS AND METHODS

Simcenter STAR-CCM+ allows using the Volume of Fluid method (VOF) and the Discrete Element Method (DEM) to model technological processes. VOF and DEM are two distinct methods for modelling physical processes. However, both were used to model the interaction of the tillage working body with the soil. The VOF is a numerical free-surface approximation method used to model fluid motion and its interaction with solids. The DEM is a numerical method used to model the behaviour of numerous discrete solids, such as particles of soil, sand, or rock. When modelling the work process of the tillage working body, the VOF can be used under the assumption that the soil is a liquid with appropriate physical and mechanical properties. On the other hand, the DEM can be used to model the interaction of a working body with individual soil particles that have varied sizes, shapes, and physical and mechanical properties.

The most common tillage implements for evaluating the use of VOF and DEM for simulating their interaction with the soil were chosen as follows: a tooth of a duck-foot cultivator, a disc harrow on an elastic rack, a subsoil cultivator (chisel plough), a mouldboard plough, and a smooth roller. The geometric dimensions of the specified tillage working bodies are presented in Figure 1.

In Simcenter STAR-CCM+, 3D models of working organs were transformed into a volume-surface mesh. Surface mesh generator and trimmer were picked as the mesh models. The 3D mesh model uses a template mesh that is constructed from hexagonal cells of the target size, from which it cuts or trims the base mesh using the initial input surface. The basic size of the mesh was taken as 0.01 m. The general appearance of the formed grids of working bodies is presented in Fig. 1.

The following physical models are selected for the VOF method in Simcenter STAR-CCM+: three-dimensional, non-stationary implicit, multiphase, multiphase interaction, separated flow, turbulent motion, k-ε turbulence model, the volume-of-fluid method, the volume-of-fluid waves, gravity. Air and soil were picked as Euler phases. A gas model with a constant density and a turbulent flow regime was picked for air. Physical and mechanical properties of air: density – 1.18415 kg/m^3; dynamic viscosity – $1.85508 \cdot 10^{-5}$ Pa·s. A liquid model with a constant density and a turbulent flow regime was picked for the soil. According to K.A. Aikins *et al.* (2023), the physical and mechanical properties of the soil are as follows: density – 1,500 kg/m^3; dynamic viscosity – 10^5 Pa·s. A random distribution of surface roughness is adopted for the VOF wave model. The general view of the modelling area with the specified geometric dimensions is presented in Figure 2.

The relative unevenness of the soil surface at rest of the VOF wave was within -0.02 m to 0.02 m, and its distribution is presented in Figure 3.

The following physical models were picked for the DEM in Simcenter STAR-CCM+: three-dimensional, non-stationary implicit, Lagrangian multiphase, multiphase interaction, gravity. The DEM particles with the following models are chosen as the Lagrangian phase: spherical particle, solid, constant density. As physical and mechanical properties of soil particles according to O.P. Hutsol & V.P. Kovbasa (2016), I.A. Shevchenko (2016), the following were adopted: density – 1,500 kg/m³; Poisson's ratio – 0.41; Young's modulus of elasticity – 1.5·10⁷. For particle-particle interaction, the following coefficient of rest friction was accepted: 1.732; normal and tangent coefficients of recovery – 0.5; linear coupling factor – 1.5; work of cohesion – 0.5 N/m. For the interaction between the particle and the steel wall of the working body, the coefficient of friction at rest was 0.61; normal and tangent coefficients of recovery – 0.5; no linear coupling. According to I.A. Shevchenko (2016), the fractional composition of the soil obeyed a normal Gaussian distribution within 10 mm to 36 mm. The accepted distribution of soil particles by size is presented in Figure 4. The soil was divided into 30 layers with a thickness of 0.02 m.

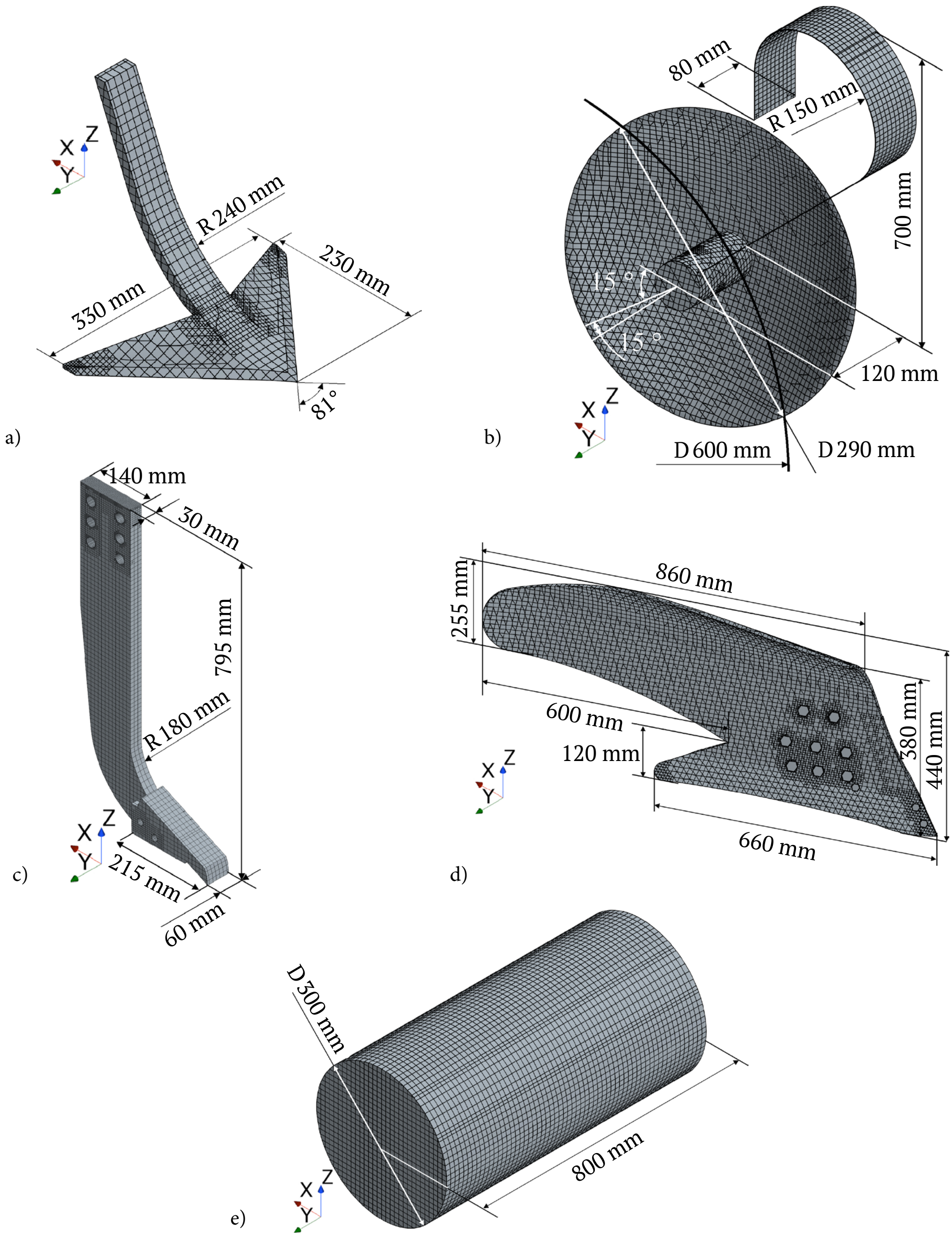

Figure 1. Geometric dimensions and formed grids of tillage working bodies

Notes: a) – tooth of a duck-foot cultivator; b) – disc harrow on an elastic rack; c) – subsoil cultivator; d) – mouldboard plough; e) – smooth roller

Source: developed by the authors

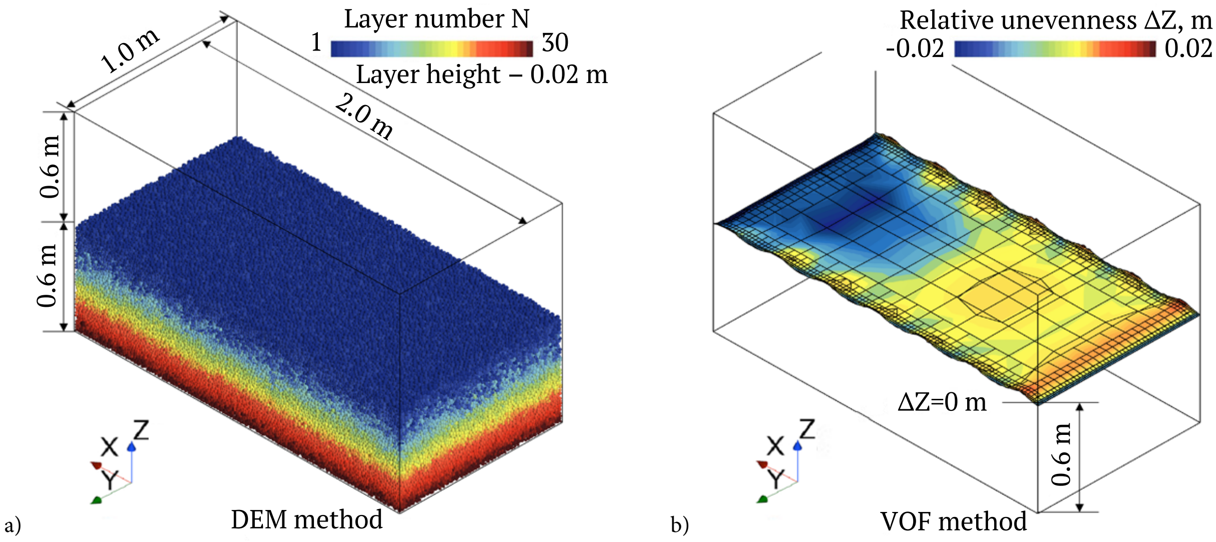

Figure 2. General view of the modelling area with specified geometric dimensions
Source: developed by the authors

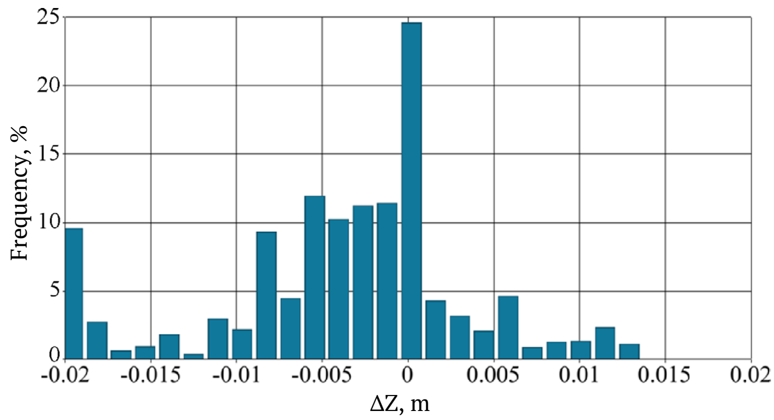

Figure 3. Distribution of the relative unevenness of the soil surface at rest of the VOF wave
Source: developed by the authors

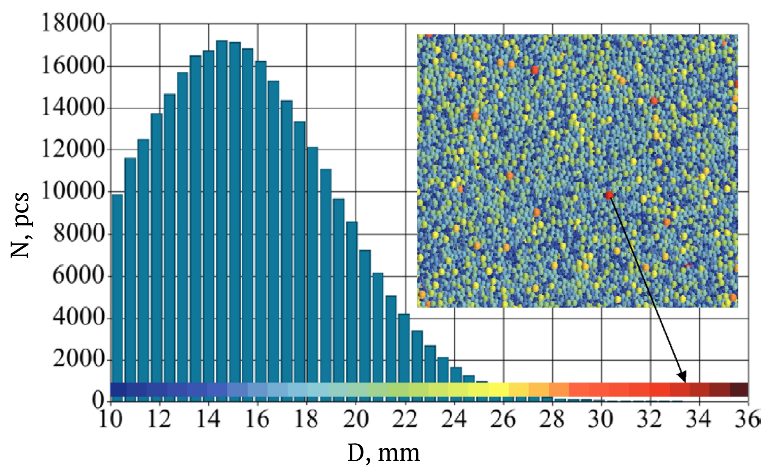

Figure 4. Distribution of spherical DEM soil particles by size
Source: developed by the authors based on I.A. Shevchenko (2016)

The parameters of the non-stationary implicit solver Simcenter STAR-CCM+ were as follows: time step – 0.01 s; the maximum number of iterations in one step – 5; 1st order of time sampling accuracy. The minimum and maximum Courant numbers – 0.2 and 0.5, respectively, – were chosen for Lagrangian multiphase. The total simulation time – 10 s.

RESULTS AND DISCUSSION

As a result of the simulation of the interaction of the tooth of a duck-foot cultivator with the soil, corresponding visualizations were built for the two methods, which are presented in Figure 5. The depth of cultivation – 0.08 m, the speed of movement – 3 m/s. The distribution of the velocities of soil particles in the DEM modelling and non-primary soil flow relative to the working body in the VOF modelling are presented in Figure 6. Figures 5 and 6 clearly demonstrate the same nature of the change in the shape of the soil surface and its movement. Thus, according to the VOF, it is possible to determine the height of the formed ridge on the soil surface, which shows its loosening. In turn, DEM can be used to determine the trajectory of the movement of individual soil particles of different diameters and to investigate the displacement of horizontal layers in depth.

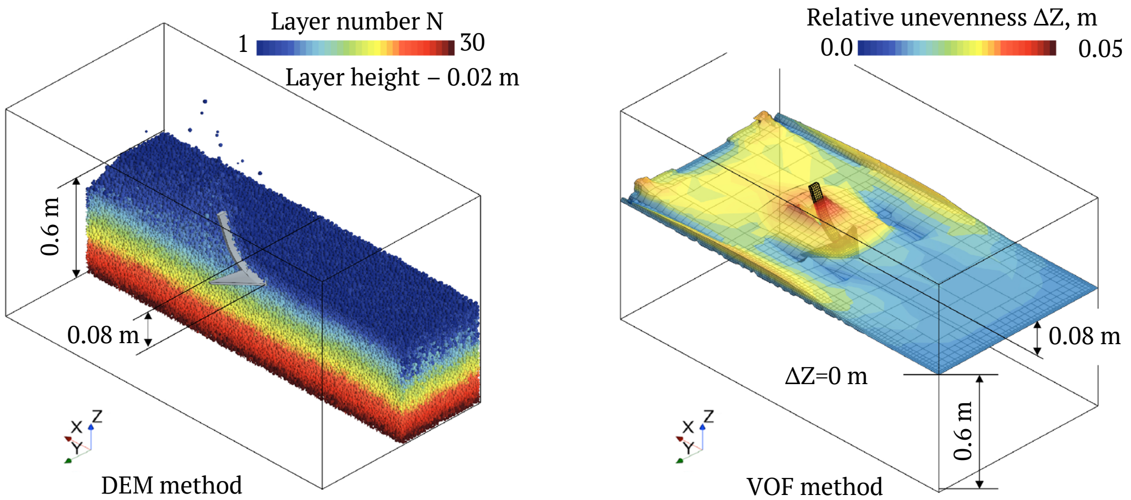

Figure 5. Visualization of the process of the interaction of the tooth of a duck-foot cultivator with the soil
Source: developed by the authors

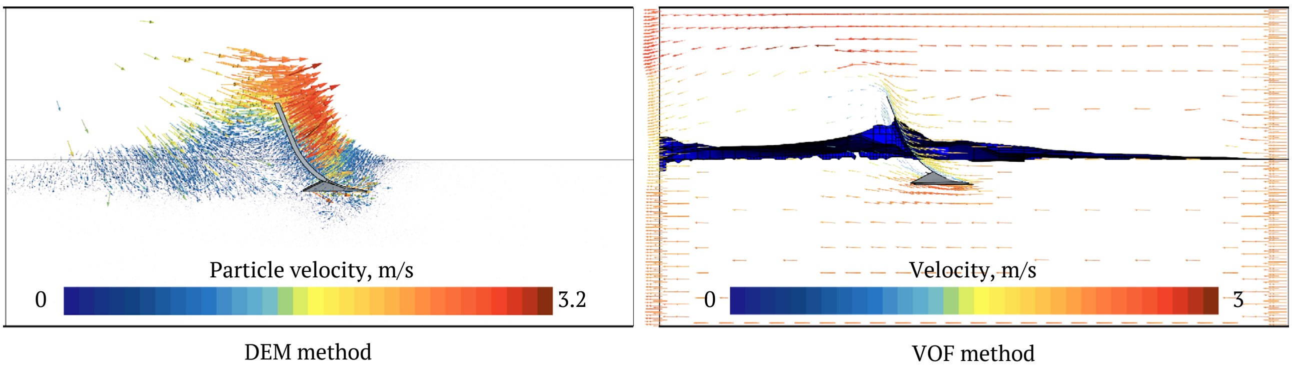

Figure 6. Distribution of soil particle velocities in DEM modelling and non-primary soil flow relative to the cultivator's arrow foot in the VOF modelling
Source: developed by the authors

Each of the methods plays a vital role in determining the numerical values of the interaction of the tooth of a duck-foot cultivator with the soil. Thus, Figure 7 shows the distribution of the forces of interaction of the duck-foot cultivator's tooth surface on individual soil particles according to the DEM. The force of interaction of soil particles varied up to 20 N. During VOF modelling, the pressure distribution on the surface of the duck-foot cultivator's tooth was obtained. The pressure reached up to 144 kPa. The given two distributions complement each other in the numerical description of the interaction process. The use of both methods at the same time allows considering the interaction of the cultivating working body (duck-foot cultivator's tooth) with the soil considering the energy and quality indicators of the work, which helps substantiate its geometric parameters. Minimizing normal stresses will help reduce the rate of wear of the working body. The best loosening of the soil is carried out through deformations of stretching, displacement, and bending, which underlies the development of the criterion for optimizing this process.

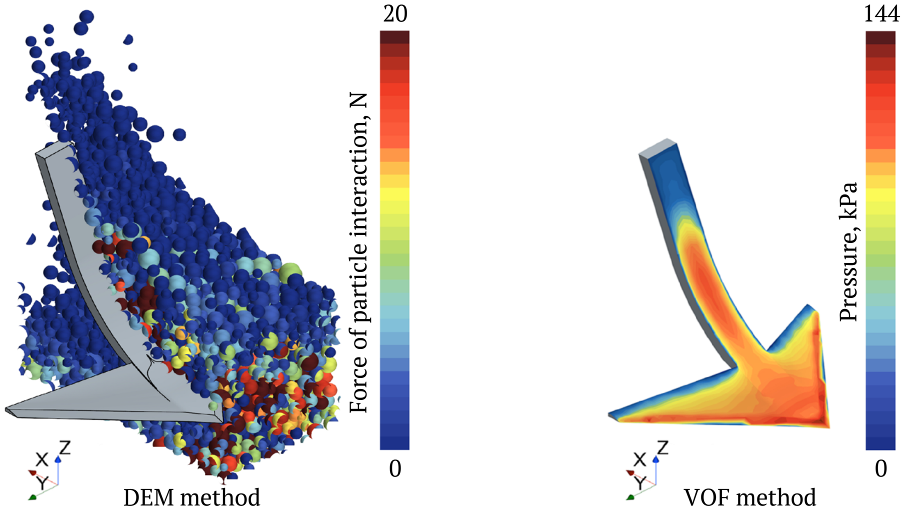

Figure 7. Distribution of the force of interaction of soil particles according to the DEM and pressure on the surface of the tooth of a duck-foot cultivator according to the VOF
Source: developed by the authors

Therefore, to achieve the criterion of strength, minimum rate of wear of the working body and uniform (isotropic) deformations in all directions, it is necessary to determine the geometric shape of the surface of the duck-foot cultivator's tooth, considering the conditions of interaction of the working body with the soil using Simcenter STAR-CCM+. The next working body is a disc harrow on an elastic stand. The depth of cultivation – 0.18 m. The speed of movement – 3 m/s. The angles of attack and inclination of the disc are taken as 15°.

For two methods of modelling the process of interaction between the disc surface and the soil, corresponding visualizations were created based on the simulation results (Fig. 8).

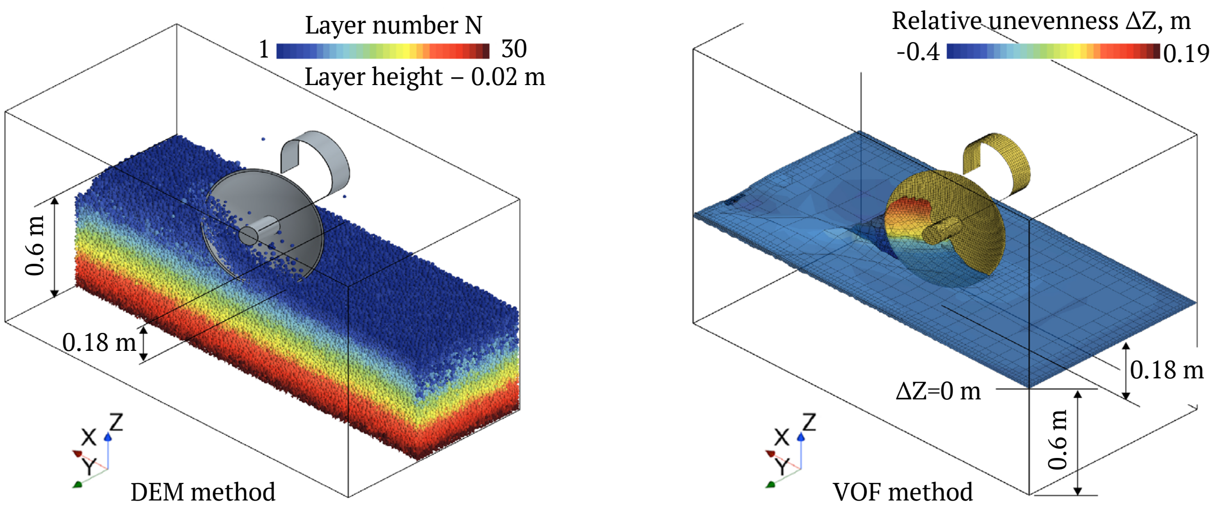

Figure 8. Visualization of the process of interaction of the disc with the soil
Source: developed by the authors

The distribution of soil particle velocities by the DEM and the VOF are presented in Figure 9. The visualizations demonstrate a similar change in the shape of the soil surface and its movement. Using the VOF, it is possible to determine the height of soil creep on the disc (0.19 m) and the maximum furrow depth (0.04 m). In turn, DEM helps investigate the formation of ridges and furrows already after the passage of the disc.

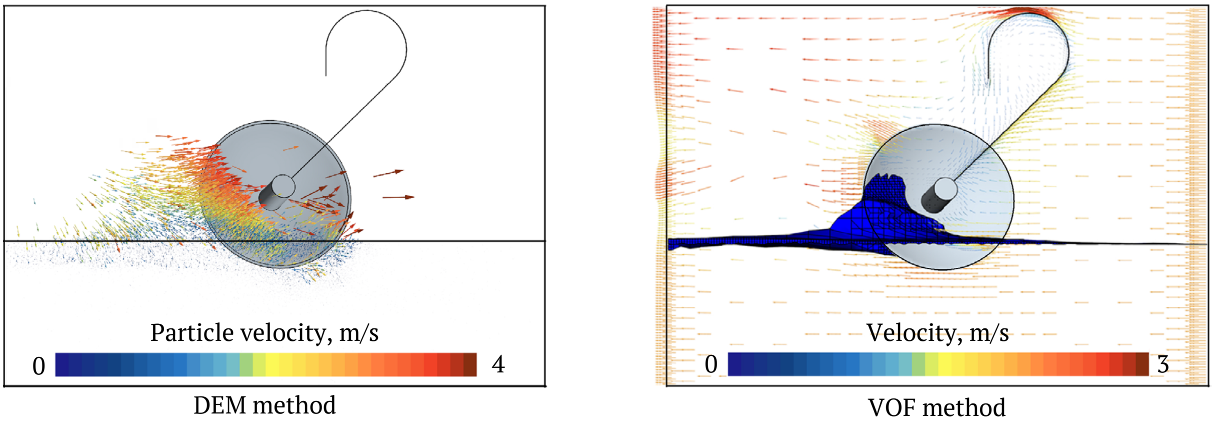

Figure 9. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the disc harrow in the VOF modelling

Source: developed by the authors

Figure 10 shows the distribution of interaction forces between the disc surface and individual soil particles according to the DEM. The force of interaction of soil particles varied up to 20 N. During the VOF modelling, the pressure distribution on the disc surface was obtained (Fig. 10). Therewith, the pressure reached 112 kPa. These two distributions complement each other in the numerical description of the interaction.

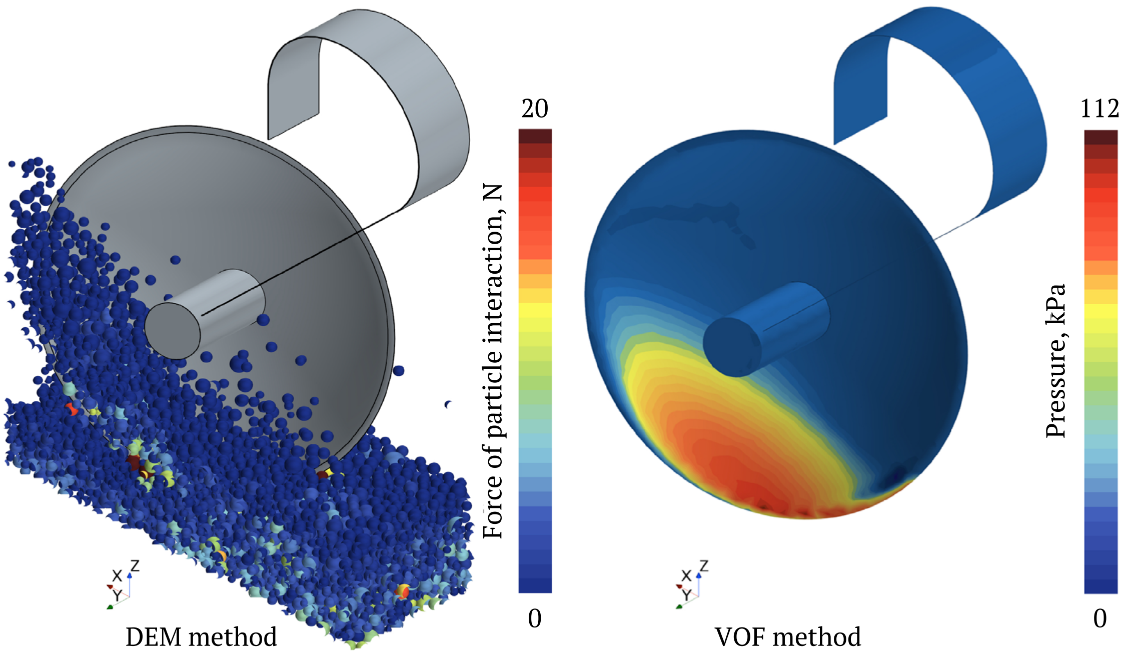

Figure 10. Distributions of interaction forces between soil particles according to the DEM and pressure on the disc surface according to the VOF

Source: developed by the authors

The use of the proposed DEM and VOF methods will allow substantiating the design and technological parameters of the disc harrow. To fulfil this purpose, it is necessary to conduct a study of soil movement on the surface of the disc harrow's working body and determine the line and area of contact with the soil environment. Subsequently, considering the stresses that arise in the soil under the action of the disk working body, it is possible to determine the components of the resistance forces. Proceeding from the distribution of unevenness of the soil surface, it is possible to determine the coefficient of soil structure and the indicator of its looseness.

The next tool is a subsoil cultivator (chisel plough) with a working depth of 0.35 m and a movement speed of 3 m/s. For two methods of modelling the interaction of the disk surface with the soil, corresponding visualizations were created based on the simulation results, which are presented in Figure 11.

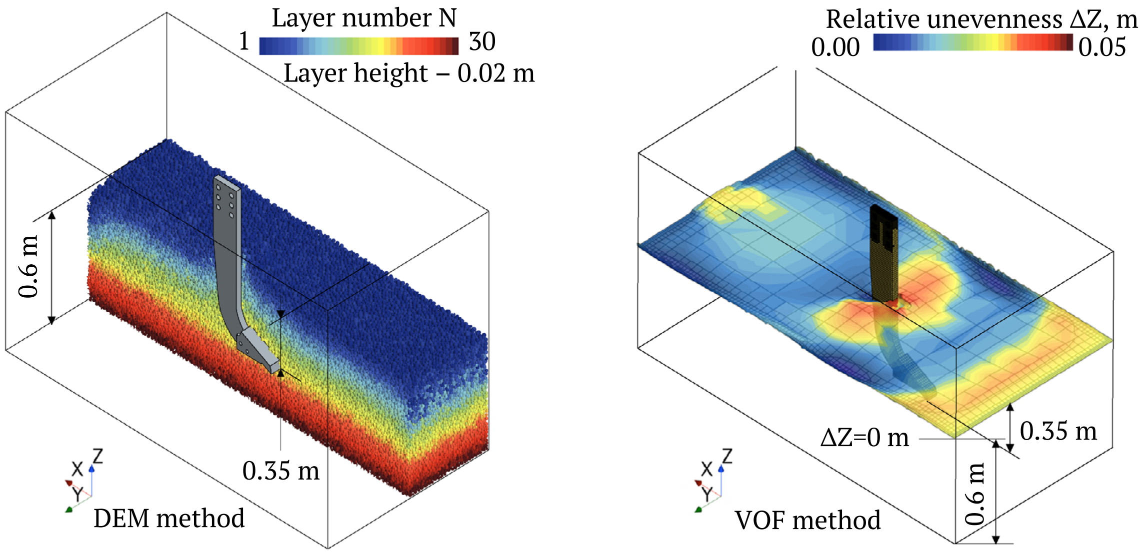

Figure 11. Visualization of the interaction of the subsoil cultivator (chisel plough) with the soil
Source: developed by the authors

Figure 12 shows the distribution of soil particle velocities according to DEM and VOF. Visualization shows a similar change in the shape of the soil surface and its movement. The use of DEM allows investigating the loosening and formation of ridges because of the lifting of soil layers after the passage of a chisel plough.

The VOF allows determining the maximum height of ridges (0.05 m).

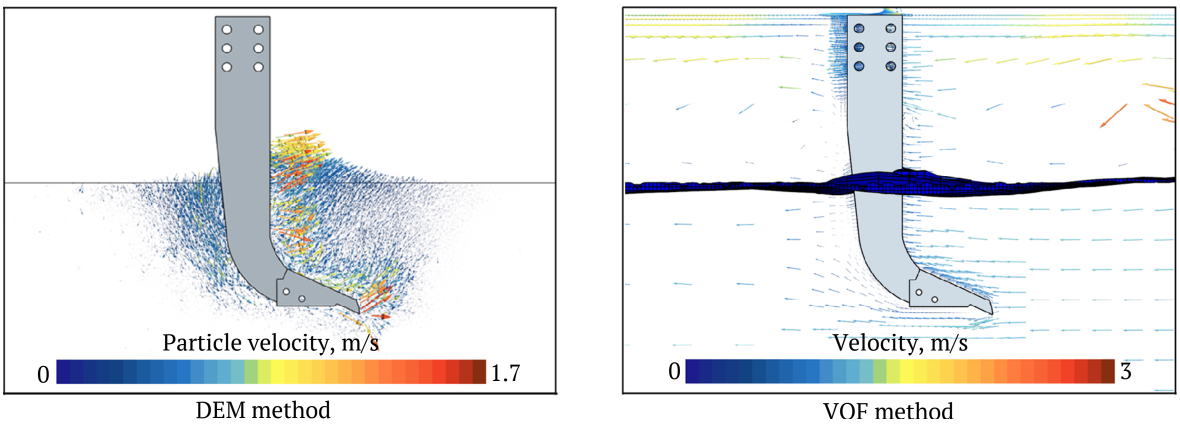

Figure 12. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the subsoil cultivator in the VOF modelling
Source: developed by the authors

Figure 13 shows the pressure distribution on the surface of the VOF chisel plough, the maximum value of which is 196 kPa. Using the DEM, the distribution of interaction forces between individual soil particles and the surface of the chisel plough was obtained. The force of interaction of soil particles varied up to 40 N.

The study of the interaction of the chisel plough with the soil allows determining the distribution of stress on the working body and the path of soil compaction. Furthermore, it is possible to calculate the soil loosening quality factor. As a result of the simulation of the interaction of the plough with the soil for the two methods, the corresponding visualizations were built, which are presented in Figure 14. The depth of cultivation is 0.3 m. The speed of movement is 2 m/s. The distribution of velocities of soil particles in the DEM modelling and non-primary soil flow relative to the working body in the VOF modelling are presented in Figure 15. Figures 14 and 15 clearly demonstrate the same nature of the change in the shape of the soil surface and its overturning. Thus, the height of the formed ridge on the soil surface can be determined according to the VOF. In turn, the DEM can be used to determine the redistribution of layers of soil particles of different diameters along the cultivation depth.

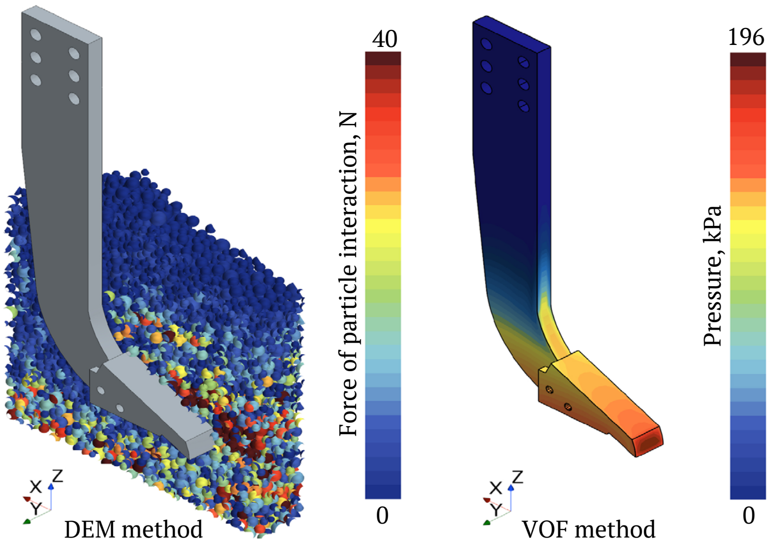

Figure 13. Distributions of interaction forces between soil particles according to the DEM and pressure on the chisel plough surface according to the VOF

Source: developed by the authors

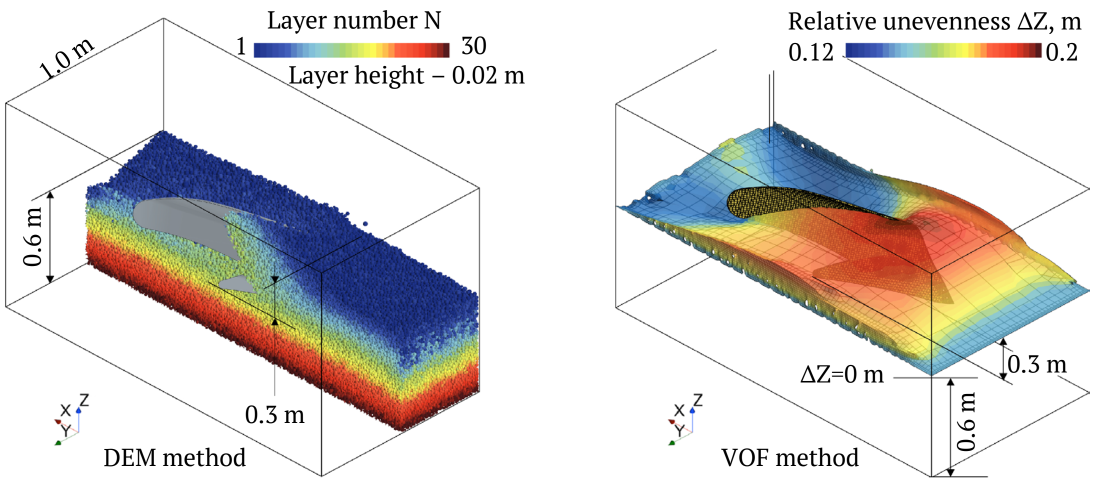

Figure 14. Visualization of the interaction between the plough and the soil

Source: developed by the authors

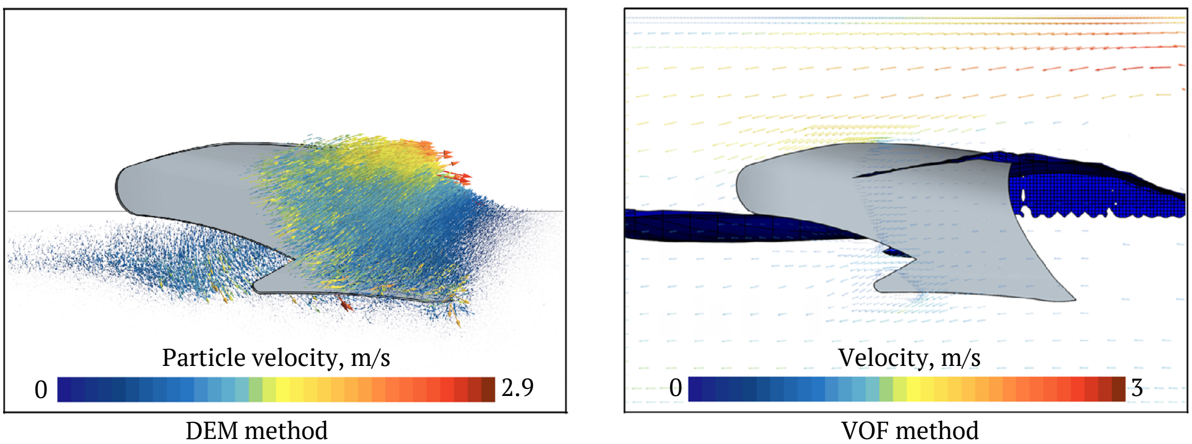

Figure 15. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the mouldboard plough in the VOF modelling

Source: developed by the authors

Figure 16 shows the distribution of the interaction forces of the plough surface on individual soil particles according to the DEM. The force of interaction of soil particles varied up to 40 N. During the VOF modelling, the pressure distribution on the surface of the plough was obtained (Fig. 16). The pressure reached up to 232 kPa.

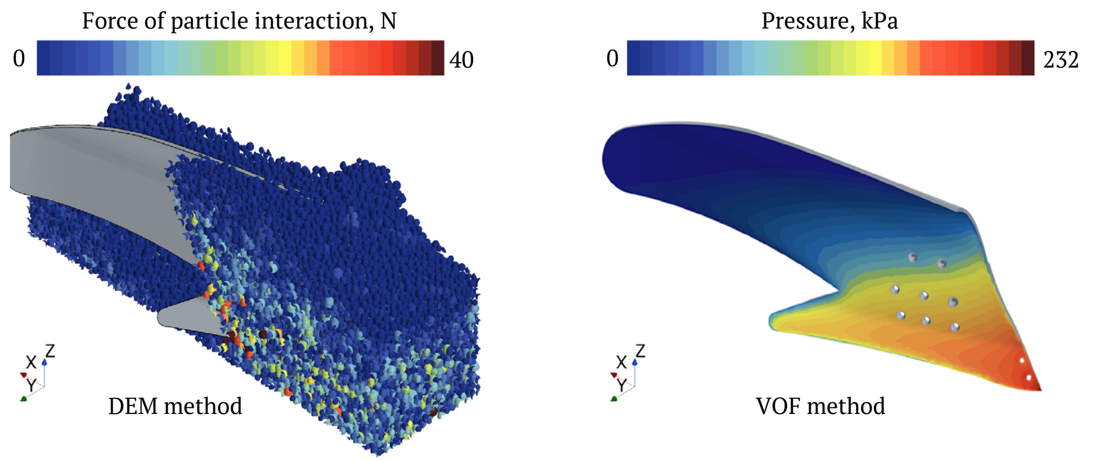

Figure 16. Distribution of forces of interaction of soil particles according to the DEM and pressure on the surface of the fallow plough according to the VOF
Source: developed by the authors

The last working body considered in this paper is a smooth roller. The speed of movement is 2 m/s. For two methods of modelling the interaction between the surface of a smooth roller and the soil, the corresponding visualizations were created based on the simulation results (Fig. 17).

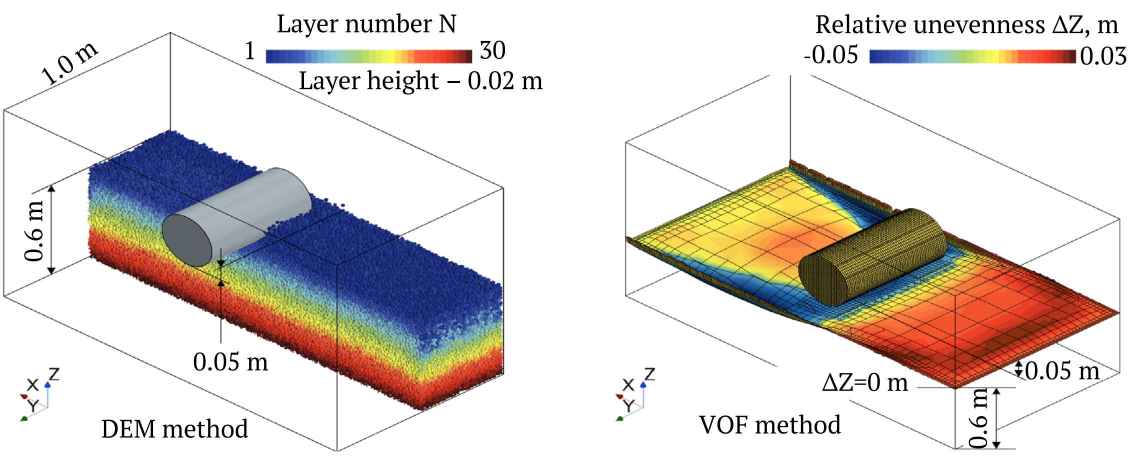

Figure 17. Visualization of the interaction between the plough and the soil
Source: developed by the authors

The distribution of soil particle velocities by the DEM and VOF is presented in Figure 18. Visualizations in Figures 17 and 18 demonstrate the deformation of the surface layer of the soil, which allows determining the degree of crushing of soil clods, destruction of the surface crust and compaction of the upper arable layer.

One of the main functions of rollers is to create a rational and uniform soil density in the soil. To fulfil these requirements by working bodies for rolling, it is necessary to know the pattern of pressure distribution at the "working body – soil" boundary. Figure 19 shows the distribution of interaction forces between the surface of a smooth roller and individual soil particles according to the DEM. The force of soil particle interaction varied up to 40 N. During the VOF modelling, the pressure distribution on the surface of the roller was obtained. Therewith, the pressure reached 48 kPa.

Comparing the obtained results with classical analytical models of A.S. Kushnarev (2010), O.P. Hutsol & V.P. Kovbasa (2016) and I.A. Shevchenko (2016) established that the values of the maximum forces of interaction between the soil and the surface of the working bodies coincide. However, the presented models help obtain the distribution of this force on the surface of the tillage tool. This greatly expands the possibilities of numerical modelling compared to classical analytical models. Furthermore, the time to calculate the forces in numerical modelling is much shorter than in the application of analytical models. The results of the study confirm the conclusions of solving the geometric problems of the sketch geometry of determining the height of the ridges above the bottom of the furrow during soil cultivation, proposed by M.V. Bakum & D.A. Yashchuk (2011). However, the geometric problems in M.V. Bakum & D.A. Yashchuk (2011) are designed for standard tillage implements. That is, with specific forms of the surfaces of working bodies, they require correction, unlike numerical modelling according to the DEM and VOF methods.

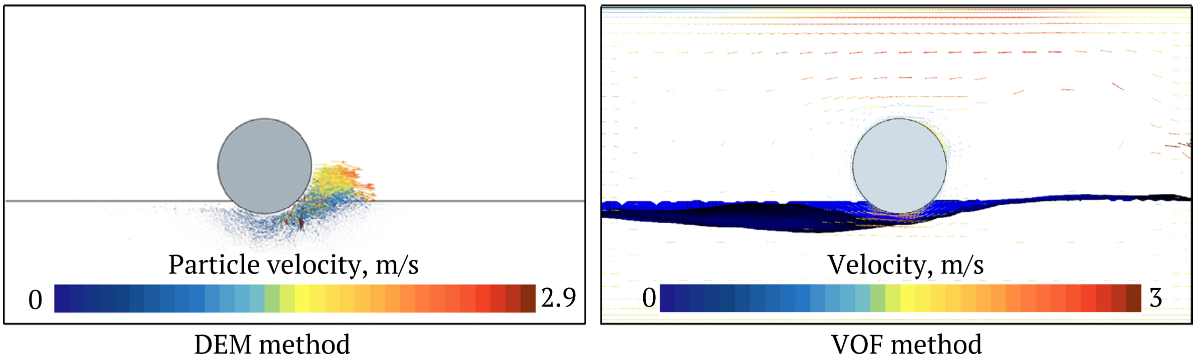

Figure 18. Distribution of soil particle velocities in the DEM modelling and non-primary soil flow relative to the roller in the VOF modelling
Source: developed by the authors

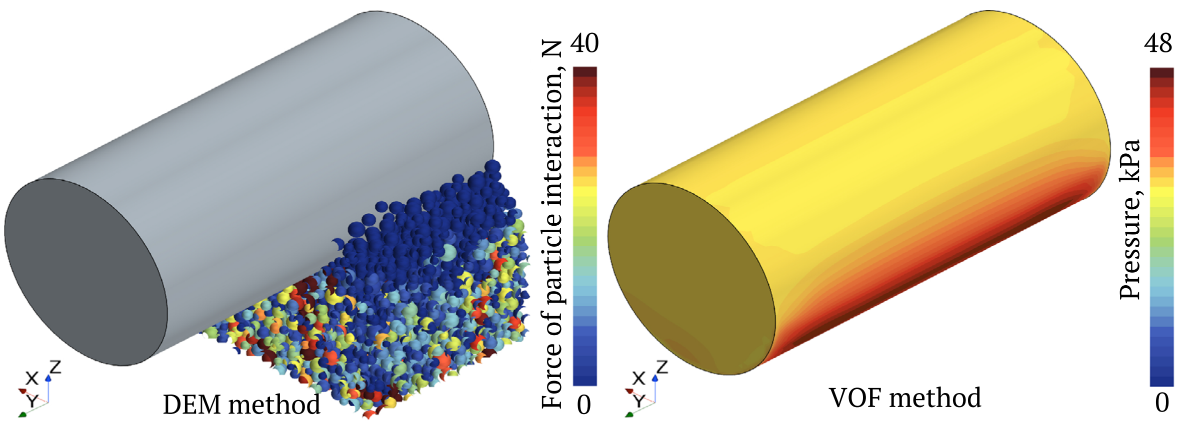

Figure 19. Distribution of the force of interaction of soil particles according to the DEM and pressure on the surface of a smooth roller according to the VOF
Source: developed by the authors

Comparison of the obtained results with those obtained by T. Okayasu *et al.* (2012), M. Ucgul *et al.* (2016), J.B. Barr *et al.* (2019) confirm the possibilities of using the DEM method for modelling the interaction of working bodies with the soil. However, as in the mentioned studies, as well as in the conducted ones, there is a need to determine the pressure on the surface of the working body. This can be done using the VOF method, which complements the picture of the physics of the interaction of the tillage working body with the soil. The models and simulations that were built by A. Ibrahimi *et al.* (2015) and J. Zhang *et al.* (2023) are confirmed by field experiments. However, the high accuracy of the models and the truth of their verification is possible only when the physical and mechanical properties of the soil, the initial and boundary conditions of modelling, which fully correspond to the field conditions, are specified. Therefore, in the presented materials, an emphasis is placed on conducting more laboratory studies to determine the physical and mechanical properties of the soil, which will allow bringing the soil model closer to real conditions.

Comparing the obtained results with the study by A.A. Tagar *et al.* (2015) reveals one drawback of the DEM and VOF soil modelling – the breakdown of soil aggregates into smaller particles and dust. This drawback can be solved by applying the Euler-to-Lagrangian transition model. Simcenter STAR-CCM+ provides the "Resolved Eulerian-Lagrangian Transition" model as a phase interaction, which allows capturing the breakup of a liquid with the formation of droplets separating from a free surface. This model is intended to be used as part of a hybrid multiphase approach where the VOF model is used alongside a Lagrangian multiphase (LMP) model. This modelling strategy allows maintaining Euler's phase accuracy in areas where it is needed locally, while using the more computationally efficient LMP model for DEM particle tracking.

CONCLUSIONS

Modelling and review of the interaction of the most common tillage working bodies (tooth of a duck-foot cultivator, disc harrow on an elastic rack, subsoil cultivator (chisel plough), mouldboard plough, and smooth roller) with the soil using the capabilities of Simcenter STAR-CCM+ according to the volume-of-fluid method (VOF) and the discrete element method (DEM). When creating the model, the main physical and mechanical properties of the soil were used (density, Poisson's ratio, Young's modulus of elasticity, coefficient of rest friction between soil particles, normal and tangent coefficients of recovery, coefficient of linear coupling, work of cohesion, coefficient of rest friction of soil particles against the surface of the working body, fractional composition of the soil). To improve the accuracy of the soil model of several types, it is necessary to conduct more laboratory studies to determine their properties and compare them with the parameters specified in Simcenter STAR-CCM+.

Simcenter STAR-CCM+ simulation of the interaction of tillage working bodies with the soil helps visualize it, determine the speed distributions of soil particles in the DEM modelling and non-primary soil flow relative to the working body in the VOF modelling. Furthermore, it is possible to determine the distribution of the force of interaction of soil particles using the DEM method, the pressure on the surface of the working body using the VOF method, the height of the formed ridges and the depth of furrows and their location in space.

In general, both DEM and VOF methods can be useful for simulating the interaction of the tillage working body with the soil in Simcenter STAR-CCM+, depending on the particular situation and the problem to be solved. The VOF can be accurate for modelling large-scale processes but does not always accurately describe small-scale motion. On the other hand, the DEM method can be accurate for modelling discrete soil particles but does not always accurately describe large-scale processes. They complement each other and create a general picture of the physics of the interaction of the tillage working body with the soil. The purpose of further research is to achieve the best density of the soil, ensuring minimal normal stresses and uniform deformations in all directions using the working body of the tillage tool.

CONFLICT OF INTEREST

None.

ACKNOWLEDGEMENTS

None.

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Симуляція процесу взаємодії робочих органів ґрунтообробних машин із ґрунтом в Simcenter STAR-CCM+

Анотація. Відсутність простих аналітичних фізико-математичних моделей ускладнює дослідження процесу взаємодії ґрунтообробних робочих органів із ґрунтом при проєктуванні нових конструкцій. Для того, щоб спростити ці розрахунки в рамках інжинірингу сільськогосподарського машинобудування, необхідно використовувати програмне забезпечення, яке об'єднає напрацювання землеробської механіки. Метою дослідження було моделювання та дослідження процесу взаємодії ґрунтообробних робочих органів із ґрунтом за допомогою Simcenter STAR-CCM+. Для цього було використано метод об'ємної рідини та метод дискретних елементів. В процесі створення моделі використанні основні фізико-механічні властивості ґрунту В результаті було проведено моделювання процесу взаємодії найпоширеніших ґрунтообробних робочих органів, таких як стрілчата лапа культиватора, дискова борона на пружній стійці, глибокорозпушувач (чизельний плуг), відвальний плуг і гладкий коток, за допомогою методів об'ємної рідини та дискретних елементів. Застосування методу об'ємної рідини дозволило встановити непервинний потік ґрунту відносно робочого органу, а метод дискретних елементів дозволив визначати розподіли швидкостей та сил взаємодії частинок ґрунту. Встановлено, що обидва запропонованих методи можуть бути корисними для моделювання взаємодії ґрунтообробного робочого органу з ґрунтом в Simcenter STAR-CCM+. Доповнюючи один одного, вони створюють загальну картину фізики процесу взаємодії ґрунтообробного знаряддя із ґрунтом. За допомогою Simcenter STAR-CCM+ була зроблена візуалізація процесу взаємодії і визначено висоту сформованих гребнів і глибин борозн та їх розташування у просторі. Застосування отриманих моделей дозволить агроінженерам швидко проєктувати нові конструкції ґрунтообробних знарядь спираючись на процесі їх взаємодії із ґрунтом

Ключові слова: знаряддя; чисельне моделювання; метод об'ємної рідини; метод дискретних елементів; розподіл швидкостей; тиск