RESEARCH ON SOIL CUTTING WITH A FLAT CUTTER USING A SIMULATION MODEL

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Resume

The research aims to develop an algorithm for modelling the process of cutting an infinite volume of soil with a flat cutter in the Abaqus software package. The hypothesis of the existence of energy and volume of resistance to cutting is proposed. The analysis of shock wave distribution in the soil volume is performed. Boundary conditions for the soil volume model are determined, as well as for a flat cutter with linear motion. Stress gradients in the soil during its deformation are determined. Confirmation of the hypothesis about the existence of energy and volume of resistance to cutting was obtained. A logarithmic regression equation was derived based on the obtained volume values.

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1 Introduction

The process of construction is a constant and continuous process that needs accurate calculations. The construction of any object starts with the zero cycle of work. It implies the development and preparation of soil for further safe construction and operation of the object. At this stage of construction, various earthmoving machines are used: excavators, bulldozers, scrapers, motor graders, draglines, and others, Figures 1, 2.

The basic principle of operation of earthmoving machines is cutting the soil with the use of a special cutting device. The soil cutting is the process of separation of soil particles as a result of the mechanical impact of the earthmoving machine's cutting device on the soil, Figure 3. Cutting of the soil is possible on dry and with the use of a clay solution. This technology is used in "wall-in-soil" construction to reinforce the walls of the excavated soil under a layer of clay thixotropic solution, which creates a dense layer and protects the trench walls from collapse.

Depending on the type of work, different working devices are used: ripper teeth, excavator buckets of shovels, dragline, loader, planer, scraper buckets, and bulldozer blades, Figures 4, 5.

For reliable operation of earthmoving machines, the design and operating parameters must be calculated. For this purpose, it is necessary to know the loads and cutting forces that act from the ground on any particular earthmoving machine's cutters and working devices. This is engaged in the theory of soil cutting. Its task is to determine the regularity of changes in the cutting force and loading of the working device of the earthmoving machine under changing conditions of cutting. Research on the loading of working devices of earthmoving machines was carried out by Zhang et al. [1], Stromblad [2], Ha et al. [3], Lee and Chang [4], Goryachkin [5], Dombrovsky [6], Zelenin [7], Vetrov [8], Kadyrov [9] and others.

Zhang et al. [1] investigated the soil-cutting process with a rotary tillage roller and the various problems arising, such as structural buckling, deformation, high energy consumption due to impacts and loads, and difficulty in observing micro changes in soil and tool behavior. They used Finite Element Method (FEM), to model a rotary cultivator with different bending angle parameters and determine the average stresses and deformation of the structure. They also established a linear relationship between the bending angle and rotary cultivator performance.

To simulate the dynamic process of soil cutting by the knife roller of the rotary tillage roller, they developed a contact model, a soil particle model, and a soil interaction model with the knife roller, using the discrete element method (DEM).

Stromblad [2] studied the distribution of loads in a multiphase medium using the finite element method. He described the installation of a tubing string into the seabed. The work presents the Coulomb-Mohr and Drucker-Prager plastic models for sand and clay. Abaqus PC was used as a calculation program.

Modelling of extreme deformations and soil structure interaction for deep-water problems using Abaqus PC was carried out by Mavrodontis [10]. His research

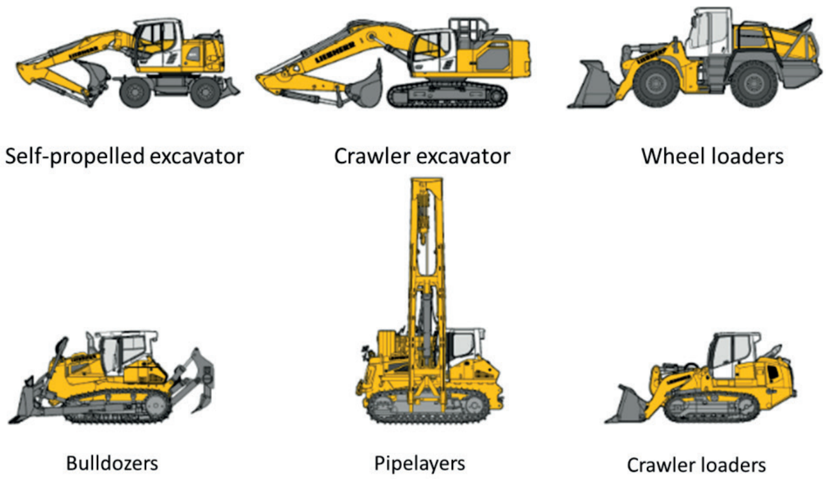

Figure 1 *Various earthmoving machines*

Figure 2 *Types of Liebherr earthmoving machines*

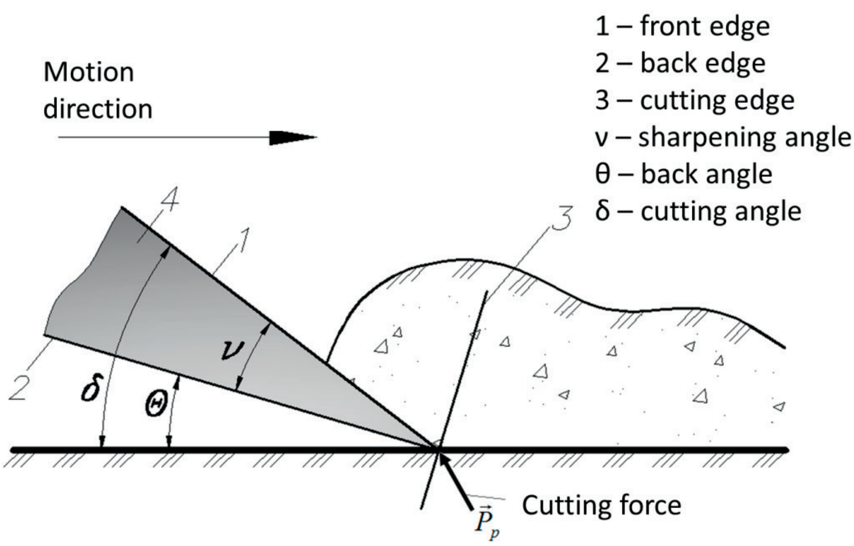

Figure 3 *Schematics of the soil cutting with a wedge-shaped cutter*

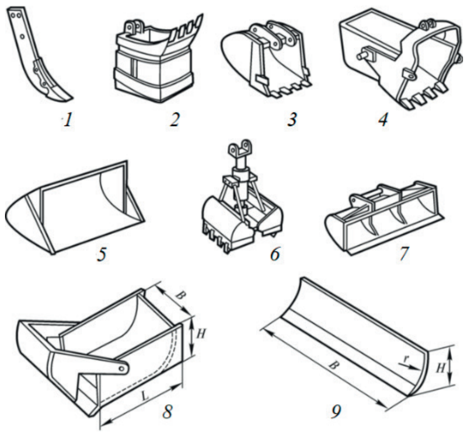

***Figure 4** Types of earthmoving machine working tools*

***Figure 5** Earthmoving with JCB single-bucket crawler excavator*

presents a model of anchor operation when sinking into the seabed. Unlike the model of Stromblad, this model is calculated by taking into account the dynamics of the process in a limited volume. The Coulomb-Mohr model was chosen as the material model.

Vetrov [8] considered the resistance to the cutting of soils as a set of resistances, depending on the cross-sectional area of the cut and the cutting perimeter. The cutting forces of a simple sharp blade, which depend on the cutting angle and thickness of the soil cut, and a complex blade, were considered. The cutting force of a complex knife was investigated as a system of simple knives that interact with each other.

Analyzing the studies on the cutting theory of various scientists, one can came to the conclusion that they use cutting forces in their works to calculate loads. In fact, forces are a physical simplification. Kadyrov [9] assumed that there is some volume that resists cutting.

Our hypothesis is to depart from the concentrated forces in working device calculations, to the mass-energy of the soil volume resisting cutting. For efficient excavation, the mass-energy of the soil volume must be less than the cutting energy. This is a new perspective on the theory of soil cutting, therefore the study could be relevant.

For research, it was decided to use the finite element model in Abaqus because this program gives reliable results and allows the investigation of many variations of cutter shapes.

The purpose of the research was to develop a finite element model, obtain stress distribution in the finite volume of soil, shock wave propagation in the finite volume of soil, and determine the volume of soil involved in the cutting resistance. To reach that purpose, the finite element method in Abaqus software was used, and the following problems were solved:

- an analytical review of methods dedicated to soil development and cutting force calculation was conducted;
- the task was set to apply the Abaqus program complex to realize the research objectives and to verify our hypothesis;
- graphs of soil deformation and stresses occurring in it during the cutting were obtained;
- gradients of strain and stress propagation in the ground during cutting were obtained;
- the volume of soil resisting cutting was obtained;
- a model of cutting of a finite volume of soil was simulated in Abaqus software.

The scientific novelty of this research consists of a new approach to the soil-cutting theory. It is based on the transition from cutting forces to the resistance energy of the soil volume.

In practice, this will avoid excessive loads on cutting

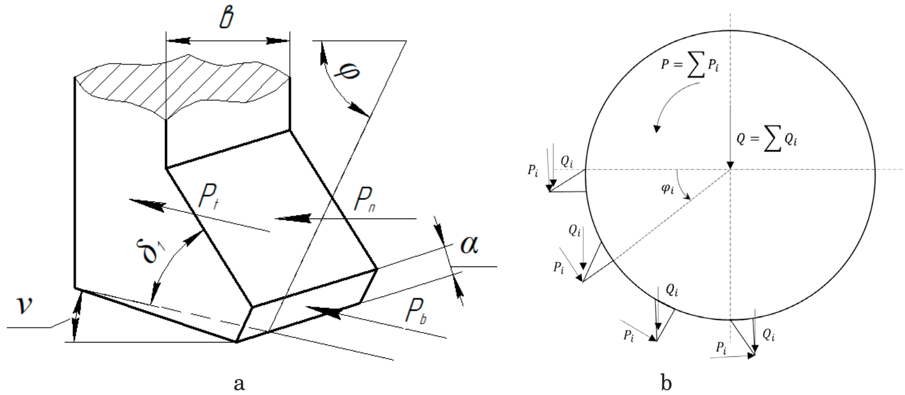

Figure 6 *Effect of cutting forces on the cutter: a) Scheme of forces applied to the cutter; b) Scheme of forces applied to the generalized model of the cutter, the tangential cutting force is labeled as P and the tool feed is labeled as Q*

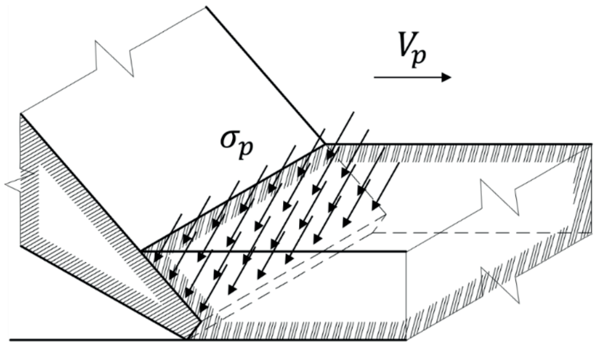

Figure 7 *The action of cutting pressure on the cutter*

tools and mechanisms of earthmoving machines. As a consequence, wear and tear will be reduced and the service life of the equipment will be increased.

2 Material and methods

In the process of cutting the soil, the entire volume of the soil is subjected to pressure from the cutter σ_c. Instead of the cutting force F_{cut}, it is proposed to use the cutting pressure σp distributed over the area of interaction of the cutter with the soil S_{cut}

$$\sigma_c = \frac{F_{cut}}{S_{cut}}. \qquad (1)$$

This pressure depends on the volume of soil involved in cutting resistance v_g and its mass m_{res}.

$$m_{res} = \rho \cdot v_g , \qquad (2)$$

where ρ is the density of the soil.

To determine this volume of resisting soil, it is necessary to know the deformation and stress damping in the soil (shear σ_{xy}, σ_{xz}, σ_{yz} or axial σ_x, σ_y, σ_z). The stress-damping boundary defines the amount of resistance to cutting.

Mathematical modelling methods were utilized, alongside the creation of a simulation model in Abaqus software and a mathematical experiment.

The calculation of soil-cutting forces with a milling machine was demonstrated by Kadyrov [9]. The forces were projected onto the tangent and normal axes, with respect to the direction of cutting, Figure 6:

$$\{P_t = \varphi bhm_{fr} + 2m_{lat}h + \eta' ahb\varphi m_{fr} P_n = (\varphi bhm_{fr} + 2m_{lat}h)ctg(\delta + \mu) + + \eta' ahb\varphi m_{fr} ctg(\delta_1 + \mu), \qquad (3)$$

where P_t - the tangential force, P_n - the normal force, φ - the coefficient accounting for the direction of the cutting angle, m_{fr} - the coefficient characterizing the specific soil resistance to cutting in the front part of the cutter, m_{lat} - the coefficient characterizing the specific force of lateral shearing of the soil by one of the lateral ribs of the cutter. δ - the cutting angle, μ - the angle of external friction between the soil and the blade, b - the cutter width, h - the chip thickness, and η' - a value equal to the coefficient ratio considering the cutter dulling to the wear area.

The lateral expansions of the shear did not take into account the specific force m_{lat}, as the soil was under the clay solution layer, Figure 7.

To calculate the cutting pressure, it is essential to convert the dependencies and coefficients derived by Kadyrov. To achieve this, the deformations and stresses in the soil during the cutting process must be determined.

A non-deformable cutter is simulated that gradually

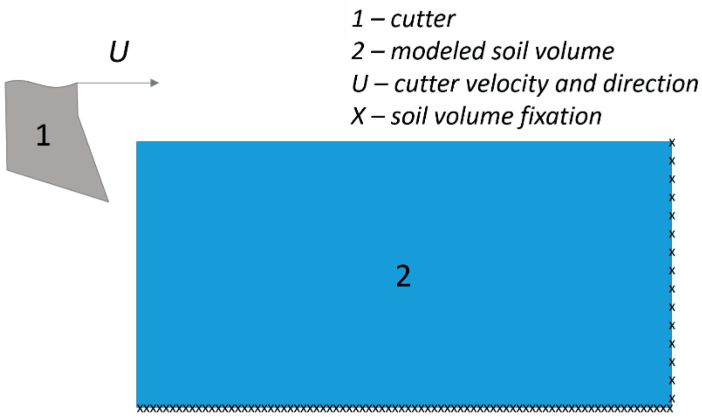

Figure 8 *Schematic diagram of the cutting model with a flat cutter*

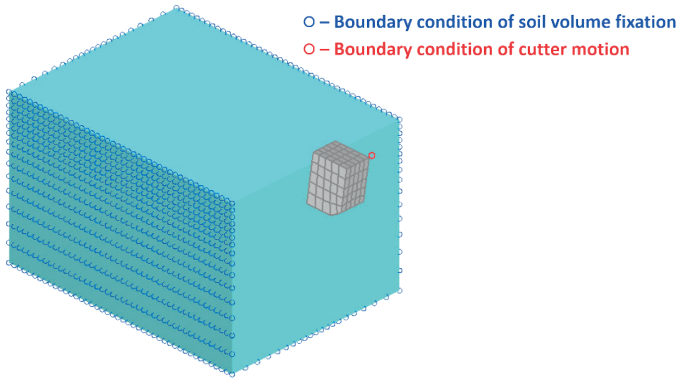

Figure 9 *Simulation model of soil deformation during the cutting with a flat cutter*

moves and eliminates a layer of soil, Figure 8.

The Abaqus software package was chosen to build the model due to its variety of tools and techniques for using the finite element method. It is based on the deformation of volumetric Lagrangian elements with elastic-plastic properties. This model explains the impact of a flat cutter on the soil during translational motion.

To evaluate the stresses, deformations, and attenuation that arise during the cutting process, we analyzed the shearing of a small amount of soil. We used elements of type C3D8R to determine the properties and geometric dimensions of the soil volume and elements of type R3D4 to give the cutter the properties of a rigid body, Figure 9 [11].

Explicit dynamic calculation (DYNAMIC, EXPLICIT) was employed in Abaqus software to model the soil deformation during the cutting with a flat cutter. It is utilized for analyzing displacements and stresses through explicit integration. The explicit integration technique involves dividing the process into many time increments and requires fewer computational resources to perform the calculations. The program automatically determines the process time step and can modify it promptly during the counting process, based on the minimum element size of the computational model, [12].

The element mass change operator (*VARIABLE MASS SCALING) is used to maintain a stable value of the time increment. This operator changes the material density within the deformed element, depending on the given time increment value. Consequently, the equilibrium condition is fulfilled, and the calculation efficiency is preserved.

Following the Abaqus guidelines, the model was constructed within a 2000 x 1500 x 1250 mm box and all the loads and deformations were confined to this volume. The cutter, being much stiffer than the soil, was not considered in the deformations. To model the cutter's geometry, the *RIGID BODY function was used to assign it the properties of a completely solid body, [12].

Boundary conditions are established in Abaqus through the use of the *BOUNDARY function. TYPE=VELOCITY was utilized to establish motion for the working device. This boundary condition specifies the velocity of movement for specific degrees of freedom and a set of nodes. The displacements were restricted using the TYPE=DISPLACEMENT category.

The Coulomb-Mohr plastic model was employed to specify the material properties of the soil. It is specified by using the *MOHR COULOMB function. This model is used to specify the yield properties for elastic-plastic materials.

Our studies are shown for a single cutter. The obtained research will be used in future studies for specific earthmoving machine workpieces.

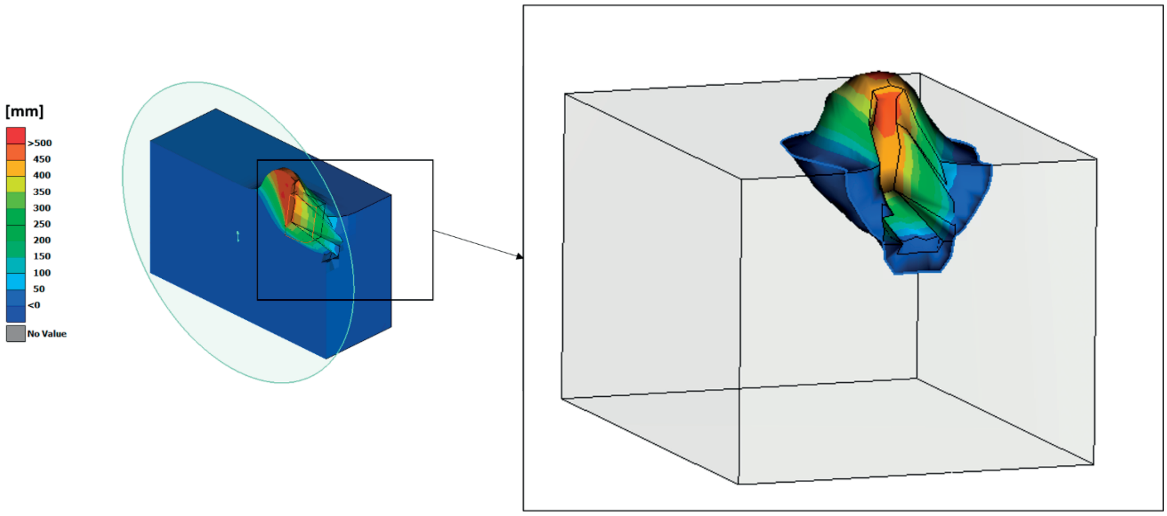

Figure 10 *Soil deformation gradient during the cutting with a flat cutter*

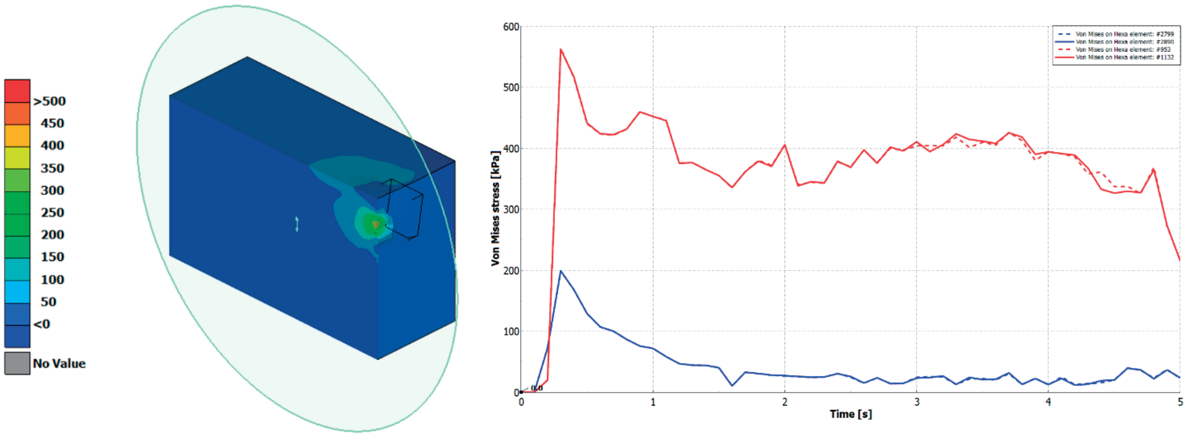

Figure 11 *Gradient and graph of stress propagation in the soil during the cutting with a flat cutter*

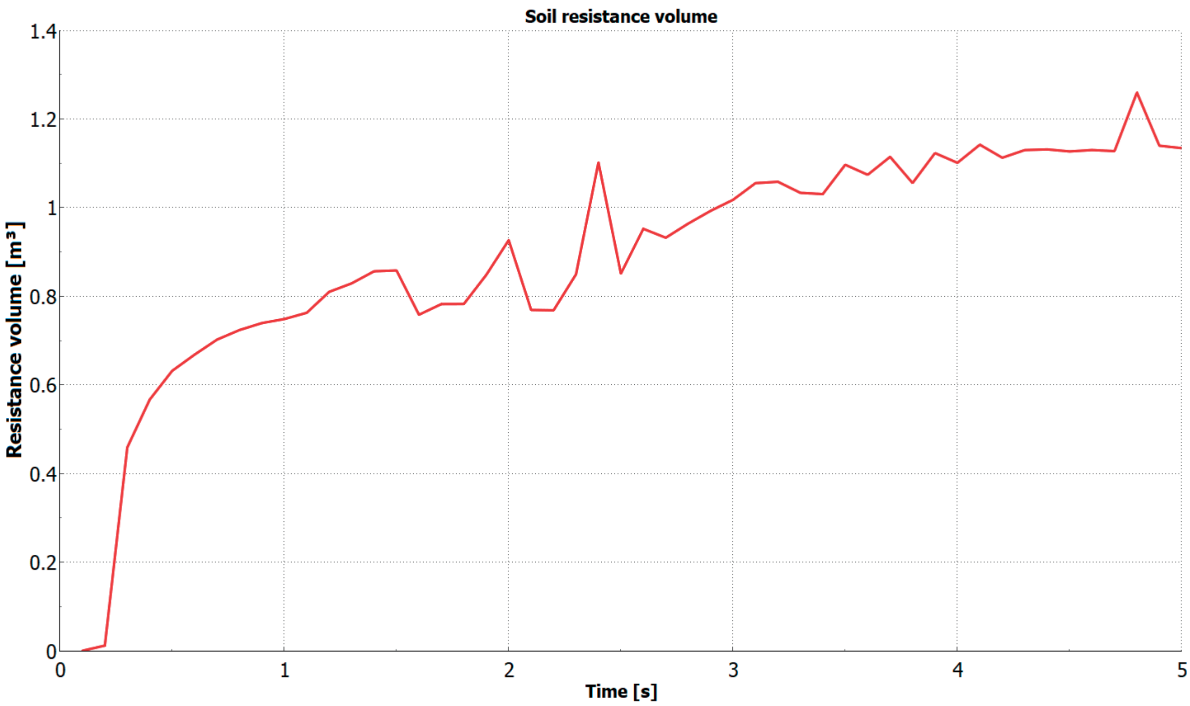

Figure 12 *Graph of the soil volume resisting cutting with a flat cutter*

3 Results

The calculation resulted in gradients and plots of strain and stress. The soil cutting visualization demonstrates a limited deformation distance, which varies based on the physical and mechanical properties of the soil for each type, Figure 10. Note that this distance does not determine the volume of soil involved in the cutting resistance; it can only be determined from the obtained stress values.

As a result of the calculation, gradients and plots of strain and stress were obtained, Figure 11. From visualization of the soil cutting, it can be seen that, the deformation has a limited distance. For each soil type, this distance will vary depending on the physical and mechanical properties of the soil. However, it does not determine the volume of soil involved in the cutting resistance. It can be determined from the stress values obtained, Figure 12.

The stress gradients show that in the process of cutting a compacted core was formed on the surface of the cutter, which negatively impacts efficiency of the soil cutting and reduces the resource of working devices of earthmoving machines, as well.

Based on the stress values obtained, the stress damping range is determined and it can be seen that when the soil is cut with a flat cutter, a much larger volume of soil resists the cutter than the deformed one. The volume can be calculated from the stress values. Therefore, any volume with a stress value less than 5% of the maximum stress value can be ignored as resistance.

The obtained volume can be converted into cutting energy for the efficient operation of the earthmoving machines. For this purpose, the dependence of the volume of resisting soil on the cutter displacement was obtained using the regression equation, Table 1.

According to the obtained auxiliary values, the regression equation is determined, Figure 13:

$$\hat{y} = 711476904.8088 + 277576243.1533 \cdot \ln x\,. \quad (4)$$

4 Conclusion

A simulation model was created using the Coulomb-Mohr model to cut a finite volume of soil with a flat working device. The calculation produced gradients and graphs depicting the soil's deformation and stresses during the cutting. The results revealed that the volume of deformed soil was significantly less than the volume of soil that resisted cutting.

Based on the results obtained, the volume of soil resisting cutting was determined, and a condition for

Table 1 *Table of auxiliary values*

i	x_i	y_i	$\ln x_i$	$\ln^2 x_i$	$y_i \ln x_i$
1	0.1	0	−2.3026	5.3019	0
2	0.2	11600000	−1.6094	2.5903	−18669479.7842
3	0.3	459000000	−1.204	1.4496	−552623517.1856
4	0.4	567000000	−0.9163	0.8396	−519536844.9726
5	0.5	632000000	−0.6931	0.4805	−438069018.1139
6	0.6	668000000	−0.5108	0.2609	−341231516.6757
7	0.7	702000000	−0.3567	0.1272	−250385810.645
8	0.8	724000000	−0.2231	0.0498	−161555931.1515
9	0.9	739000000	−0.1054	0.0111	−77861421.0711
10	1	748000000	0	0	0
			…		
40	4	1100000000	1.3863	1.9218	1524923797.2319
41	4.1	1140000000	1.411	1.9909	1608525150.0297
42	4.2	1110000000	1.4351	2.0595	1592943823.0711
43	4.3	1130000000	1.4586	2.1276	1648234975.6505
44	4.4	1130000000	1.4816	2.1952	1674213131.2444
45	4.5	1130000000	1.5041	2.2622	1699607458.3572
46	4.6	1130000000	1.5261	2.3288	1724443622.9494
47	4.7	1130000000	1.5476	2.3949	1748745634.8491
48	4.8	1260000000	1.5686	2.4606	1976456056.5714
49	4.9	1140000000	1.5892	2.5257	1811728133.8329
50	5	1130000000	1.6094	2.5903	1818664841.0505
Σ	127.5	44830600000	33.3485	60.9821	40653868702.3186

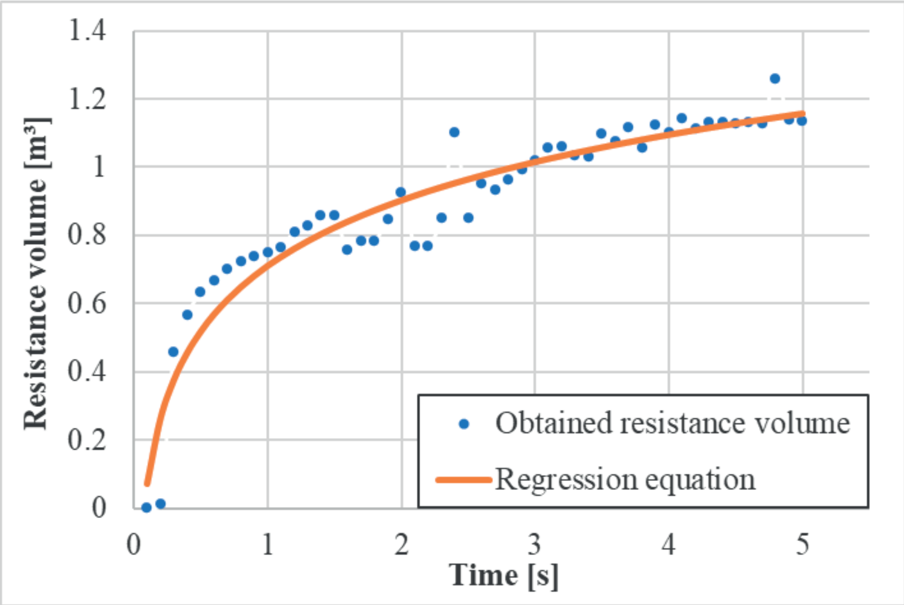

Figure 13 *Scatter diagram and graph of the regression equation*

determining this resisting soil volume was introduced. This work offers a new perspective on the classical theory of soil cutting. The obtained results confirm the hypothesis regarding the existence of a cutting resistance volume and facilitate the determination of cutting energy for the soil. Practically, this advancement will enable more effective operation of earthmoving machines by providing a better understanding of cutting dynamics and optimizing performance.

In terms of modeling specifics, the simulation incorporated a constant cutting speed, which allowed for a controlled analysis of stress distribution and soil behavior. The model also addressed the challenge of accurately representing soil deformation and resistance through calibration of the Coulomb-Mohr parameters for Abaqus Dynamic, Explicit. These considerations were crucial for obtaining reliable results and ensuring that the simulation closely reflects real-world conditions.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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