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Mathematical model of resistance to spreading forces using a bulldozer blade

Norqul Aslonov*, *Khusniddin* Irisov

University of Public Safety, Chorsu fortress, Zangiota district, Tashkent region, 100109, Uzbekistan

Abstract. The article presents an in-depth analysis of the theories of soil digging. It has been shown that the developed theory of soil digging is closely intertwined with experimental data. This makes it possible to calculate all the forces acting on the working body by a divisible sheet, including those that take into account the forces arising vertically from a moving sheet, which are determined by the refraction and the angle of the sheet cut. In order to characterize the process of processing solid waste with a bulldozer blade mathematically, it is necessary to take into account the effect of the cutting speed of the soil on the resistance to digging.

1 Introduction

One of the defining directions of increasing the efficiency of excavators is the improvement of working bodies on the basis of physical and mathematical modeling of the process of interaction of working bodies with the working environment and optimization of working equipment.

At present, the above developments of the authors can be conditionally divided into three groups of theories describing the processes of interaction of working bodies with the environment:

1. theories of experimental-empirical nature. This group of theories is based on the results of experimental studies that reveal the physical nature of the soil cutting process;
2. theories based on the basic conditions of the mechanics of the whole environment and supplemented by the condition of maximum equilibrium;
3. theories that take into account the dynamic characteristics of the interaction of the working bodies of earth moving machines with the environment.

2 Materials and methods

The first group of theories includes V.P. Goryachkina, N.G. Dombrovskiy. Russian scientists such as A.N. Zelenin, V.I. Balovnev, G.V. Kustarev [1,5,6,7] can also be included.

One of the first works on the process of cutting the soil was carried out by academician V.P. Goryachkin [5], who proposed a rational formula for determining the gravitational force

* Corresponding author: husniddin_bek@mail.ru

of the plug. Although the conclusions made by V.P. Goryachkin did not cover all aspects of the process of cutting soils, his research can be considered as the first step in the study of this process.

N.G. Dombrovsky [6] conducted research on the process of excavating the soil with excavator buckets. His research allowed him to formulate the basic rules of resistance to excavation with the working bodies of excavators. An experimental correlation was proposed by N.G. Dombrovsky to determine the resistance to excavation:

$$P = kbh, \tag{1}$$

where k – specific resistance to excavation, kg /cm2;

b – width of the path, cm;

h – thickness of the path, cm.

Dombrovsky N.G. made the assumption that the resistances depend on the cross-sectional shape of the cross-section. He described this relationship by the ratio of the length of the cutting perimeter of the bucket to the cross-sectional area of the cross-section.

$$k = f\left(\frac{L}{F_{cp}}\right), \tag{2}$$

where $\frac{L}{F_{cp}} = \frac{b+2h}{bh}$, L – length of the cutting perimeter of the bucket, cm; F_{cp} – cross-sectional area of the section, cm2.

N.G. Dombrovsky concluded that the specific resistance to excavation decreases with increasing cutting thickness and increases with increasing cutting angle.

The model (1) is not related to the analysis of the mechanism of movement of the soil in the bucket. It only reflects the description of the change in the power parameters of the bucket filling process in terms of developing a minimum cross-section of the pavement. The recommended values of specific resistances do not have a clear relationship with the bucket capacity, the number of strokes of the density meter, and the motion characteristics. The experimental value of the coefficients requires clarification with respect to the relevant types of working bodies.

A.N. Zelenin's research [7] is devoted to the geometric laws of the soil cutting process. He determined that the shear force depends on the width and depth of the crack, the cutting angle, the number of teeth on the cutting perimeter, the number of hollow surfaces of the cut, and the moisture content of the soil. A.N.Zelenin invented the tool entitled "Road Research Institute"

The strength of resistance to digging the soil with a bulldozer is determined by the following formula

$$P_k = 10Ch^{1,35}(1+2,6l)(1+0,01\alpha) + \xi K_{sj}F + gq\gamma tg\rho, \tag{3}$$

where C- Coefficient representing the number of road research institute winners;

l – length of cutting perimeter;

α – cutting angle, rejection;

ξ – soil compaction coefficient;

Ksj – specific compressive strength of the soil, N/cm2 ,

g – acceleration of gravity, m/sek2;

q – the size of the delivery prism, m3;

tgρ – the tangent of the angle of inclination of the soil components;

γ – bulk density of soil, kg/m3.

(3) analysis of the formula shows that it is largely empirical. The resistance of the soil to breaking with a knife, crushing resistance, friction on the pavement and displacement of the pushing prism are taken into account. The design diagram of the earthwork process does not reflect the real mechanism of the process, especially at the final stage.

A positive quality of the model is the ability to determine the resistance through a generalized indicator of strength, such as the number of impacts of a dynamic density meter.

Yu.A. Vetrov made a great contribution to the cutting of soils [8]. He obtained the laws of cutting complex blades of various shapes with elementary profiles. Yu.A. Vetrov proposed empirical relations for determining the tangential and normal components of the lateral force of the soil. Based on the theory of the boundary state of scattered media, developed by V.V. Sokolovsky [9,16], a lot of work has been done by Yu.A. Vetrov to develop analytical methods for calculating shear and excavation resistance. The V.V.Sokolovsky method is based on the condition of the boundary stress state of the entire soil in the frontal zone of the affected body.

The mathematical model [8,10,11,12,13] of soil shear resistance proposed by Yu.A. Vetrov has the following form:

$$P_p = \varphi m_{sb} bh + 2m\delta h^2 + 2m\delta_{sr} h, \qquad (4)$$

where φ – coefficient taking into account the cutting angle of the soil;

msb – cutting angle α = 300, corresponding specific shear force;

δ – angle of external soil friction, degrees;

m – coefficient representing the shear force along the sides of the cut soil.

The mathematical models of Yu.A. Vetrov (formula 4) and V.I. Balovnev (formula 5) allow calculating all the forces acting on the working body along a separate trajectory, including the vertical ascending moving layer, the width of which is determined by the angle of refraction and shift of the path, taking into account their strengths. This scheme more fully reflects the real process. The difference between the models is that in the Balovnev model, the cutting resistance by the side and lower blades is determined by the adhesion of the soil and the frictional force of the layer against the walls of the dump, taking into account the impermeability of the latter. In Vetrov's model, the breaking forces of the soil are determined by the empirical coefficient of shear resistivity. The latter depends on the size of the blade, the angle of installation and the size of the impermeable area of the blade. Both models fully reflect the real mechanism of the final stage of the bucket (dump) filling process. The shear properties used in both models are a generalized indicator of density - the dynamic density meter does not depend on the number of impacts and the soil resistivity to shear. The angles of friction are limited.

K.A. Artemiev [14] proposed a graphic-analytical method for determining the resistance to cutting and excavation in a scraper bucket. The influence of the cutting angle, the thickness and width of the passage, the specific parameters of the bucket on the resistivity to earthworks has been determined.

3 Results and discussion

The formula for digging the soil with a bucket working body looks like this:

$$P_k = (b + 2v_1 f\xi)tM_3 \times \left[k_4 \left(\frac{\gamma h^2}{2} + hq + hc_\omega ctg\rho\right) - hc_\omega ctg\rho \right] + 2c_\omega F_1 \cos\psi, \qquad (5)$$

where v1 – soil thickness, sm;

f – angle of friction on the groove surface of the soil, grad;

t – blade thickness, sm;

M3 – ground mass, kg;

cω – adhesion coefficient between soil particles.

K.A. Artemev's mathematical model reflects the process of breaking the soil layer under the combined action of the soil in the bucket and the blade. The angle of refraction depends on the characteristics of the soil, the thickness and height of the bucket filling. These factors determine the value of the coefficient and through it the resistance values. The moving layer is represented by a prism that expands upwards. The positive quality of the model is to take into account the decrease in the size of the refractive angle depending on the filling of the bucket, but the range of refractive angle change is much higher than that observed in the experiment.

Large experimental studies of excavation of soil by motor grader and bulldozer were carried out by I.A. Nedorezov. He proposed a formula for determining the shear resistance, taking into account the curvature of the blade.

The commonality of the first and second groups of theories is that the deformation of the medium is not taken into account even when the compressed media are considered during the excavation. In a number of studies, only the softening coefficient is introduced.

All of this work is mainly devoted to the identification of loads falling on the working body, but the authors in their study cite various computational schemes and their corresponding permissions. As a result, various mathematical models were obtained to determine the resistance to excavation and shearing of the soil (Appendix).

We consider theories related to the third group.

V L Baladinsky's scientific hypothesis [4] is that under dynamic loading conditions conditions are created for dynamic distortion, resulting not only in the area of interaction of the working body with the environment, but also outside this area due to waves of stresses propagating in the environment.

In the research of A M Zavyalov [15] the one-component plastic-compressible integral environment is considered as an environment in which the working bodies of road construction machines interact. Then the one-dimensional motion of the soil is represented by two equations: the superpositions of the equations of motion and continuity:

$$\gamma\left(\frac{\partial \vartheta}{\partial t}+\vartheta\frac{\partial \vartheta}{\partial x}\right)=-\frac{\partial P}{\partial x}, \qquad (6)$$

where x – the current coordinate of the soil particle;

t – time;

P, γ and ϑ – pressure, density and velocity of soil particles.

The analysis of the equations expressed in the above work by Zavyalov (3) makes it possible to obtain a complex of integral models of soil movement, which makes it possible to determine the strength and kinematic properties of the soil at any point in the field of movement.

The author also has a free configuration, the deepening of a solid body into the ground as a whole; formation and displacement of the terrestrial prism; cutting of soil of different moisture content with a profile of arbitrary shape; provides mathematical models for the interaction of basic processes such as bucket filling.

In the work of A.S. Slyusarev the process of interaction of the working bodies of hoisting machines with a volumetric compressible scattering material is analyzed. He developed a theory of compaction of a scattering material in a solid matrix, which allows showing the properties that determine the capacitively stressed state of the material during deformation.

All the theories of excavation mentioned above, especially the second and third groups, are designed for the same solid bodies.

Analysis of the physical and mechanical properties of solid household waste showed that they have the following properties:

- structural heterogeneity;

- poor adhesion between components;
- anisotropic and other properties.

Consequently, the application of the above theories for calculating the strength and kinematic parameters of the process of developing a SHG (solid household garbage) with a bulldozer excavator and comparing these results with experimental data gives large errors.

An in-depth analysis of soil development theories showed that prof. The soil development theory developed by V.I. Balovnev is closely related to experimental data. Model V.I. Balovnev (formula 5) allows you to calculate all the forces acting on the working body along the separated path, including the forces arising vertically from the moving layer, the width of which is determined by the angle of refraction and the section of the track. Such a scheme more fully reflects the real process, but does not take into account the influence of technological factors, in particular, the effect of the cutting speed of the soil on the effort of earthworks. For a mathematical description of the process of earthworks with a bulldozer, it is necessary to take into account the effect of the cutting speed of the soil on the resistance to earthworks. This is due to the fact that the influence of inertia forces is significant at a working speed of more than 1.5 m/s.

Numerous studies carried out by foreign scientists on the effect of shear rate on the strength of resistance to earthworks, in particular, so-called. Research by A. Semkin showed that the resistance to digging (cutting) increases with increasing cutting speed. To study this pattern, a series of experiments was carried out to determine the dependence of the cutting speed on the resistance to excavation on a specially designed physical modeling stand in the department of operation and repair of road construction equipment. The results of the experiment are shown in the Table 1.

Table 1. The values of the dynamic factor for different values of the operating speed depending on the type of environment being launched. Ranges of values of the working speed of the bulldozer.

№	The type of environment in which it is used	Bulldozer operating range, (m/s)			
		1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5
1	Mud	1.10-1.20	1.20-1.30	1.30-1.40	1.40-1.50
2	Sandy soil	1.00-1.10	1.10-1.20	1.20-1.30	1.30-1.40
3	Sand	1.00-1.10	1.00-1.10	1.20-1.30	1.20-1.30
4	Natural solid waste	1.00	1.00-1.10	1.20-1.30	1.20-1.30
5	Shredded solid household garbage	1.00-1.10	1.00-1.10	1.20-1.30	1.20-1.30

Analysis of the table shows that the coefficient of dynamic resistance depends not only on the cutting speed, but also on the type of the processed medium. The denser the medium, i.e. the stronger the structural bonds in the medium, the more energy is spent on its destruction.

$$P_{k1} = \gamma_p \cos^2 \rho \frac{BH_{np}^2}{2} + \gamma_p \cos^2 \rho \frac{(B_0 - B)H_{np}^2}{2} = \gamma_p \cos^2 \rho \frac{B_0 H_{np}^2}{2} \tag{7}$$

$$P_{k1} = k_\vartheta \gamma_p \cos^2 \rho \frac{B_0 H_{np}^2}{2}$$

where kϑ – speed coefficient, m/s.

B0 – sliding width;

H_{np}^2 – the height of the ground rise from the sliding surface.

4 Conclusion

In conclusion, the increase in engine power of cars today has led to an increase in speed coefficients.

In the process of leveling and burying solid household garbage using a bulldozer screwdriver equipped with a side expander and a vertical grid, the basic parameters of the horse were substantiated using the bulldozer gravity balance formula. In the process of leveling and burying solid household garbage using a bulldozer screwdriver equipped with a side expander and a vertical grid, the basic parameters of the horse were substantiated using the bulldozer gravity balance formula.

Mathematical models of the processes of alignment and burial of solid household garbage with a bulldozer screwdriver equipped with side expanders and a vertical grid have been developed.

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