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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ
Satbayev University

# ХАБАРЛАРЫ

# ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН
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# NEWS

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# PREDICTING THE RESISTANCE FORCE OF HOMOGENEOUS GROUND TO CUTTING

**Abstract:** a model for predicting the ground resistance to cutting is developed based on the theory of ultimate equilibrium of the bulk medium, which takes into account the configuration of the ground failure plane. The three-dimensional nature of soil destruction is estimated by the spatiality coefficient. The model uses the results of automatic identification of soil strength parameters and data from field and laboratory tests of soils. In all models, the resistance force is functionally dependent on the volume of the soil that is in the maximum stress state. Analytical expressions of the soil volume of the central wedge and lateral sickle are obtained, which allow us to analytically calculate the specific energy intensity of the soil cutting process. The correctness of the developed model is evaluated in comparison with the models obtained on the basis of the limit equilibrium, the fundamental equation of earthmoving operations and with experimental data. The dependences of the resistance force are established on the cutting modes of soils.

**Key words:** prediction of the resistance force, the fundamental equation of earthmoving works, the limit equilibrium of a loose medium, the dependence of the resistance of the volume of soil, the coefficient of spatiality, three-dimensional nature of fracture, side of the hammer, a Central wedge, the volume of soil in limit equilibrium.

**Introduction.** Present time, there is a tendency to automate the management of soil digging by earthmoving machines, in particular hydraulic excavators. For these purposes, the parameters of soil strength properties are identified automatically, and analytical models are developed for predicting soil resistance to cutting. Planning the trajectory of the excavator's working equipment depends on the accuracy of analytical models. Based on the results of trial digging, a map of the area is formed with soil data in digital format. Soil conditions are formed from homogeneous soils, and from soils containing solid clastic-stone inclusions that violate the uniformity, stress state of the soil.

Analytical are known two-dimensional and three-dimensional models for predicting the strength of soil resistance of cutting, developed on the basis of the theory of limit equilibrium of a loose medium and on the basis of the fundamental equation of earthmoving operations.

V.V. Sokolovsky (1954) the value of the components of the passive soil pressure on the surface of the cutting element is determined taking into account the shape of the sliding lines of the soil volume in the limit equilibrium. Based on it, two-dimensional and three-dimensional models for predicting the ground resistance to cutting have been developed [2-6]. For calculations, soil data can be used for laboratory tests, for cutting soil in the field, and for automatic identification of soil strength parameters [7-10].

A characteristic feature for two-dimensional, three-dimensional models developed on the basis of the fundamental equation of earthmoving works is that the shape of the zone of soil destruction is unknown in advance, and its unfavorable position is determined from the principle of the minimum values of the coefficients $N$ in the fundamental equation of A. Rees (1965) [13-22].

**The aim of the study** is to develop an analytical model for predicting the strength of ground resistance of cutting, which has sufficient accuracy for practice. The model uses the results of automatic identification of soil strength parameters, data from field and laboratory tests of soils.

**Methodology.** When developing the model, the following methodological assumptions are used:
- the maximum value of the ground resistance of cutting functionally depends on the volume of the soil in the maximum stress state;

- the cutting path of the soil is horizontal; the cutting thickness is constant with the formation of element chips.

**Development of the model.** We have developed a three-dimensional model of the interaction of the cutting element with the ground based on the method [1], subject to the conditions of geometric similarity, due to the difficulty of taking into account all the many factors that affect the process of cutting the soil, the analytical determination of the resistance force of the soil of cutting is made approximately. In the developed model, the influence of the cutting speed of the soil is not taken into account, due to the fact that the ranges of changes in the cutting speed observed in production conditions do not cause the appearance of viscosity in the soil. Most earthmoving machines develop the soil on the principle of cutting a certain thickness of chips from the soil mass (Fig. 1) [2].

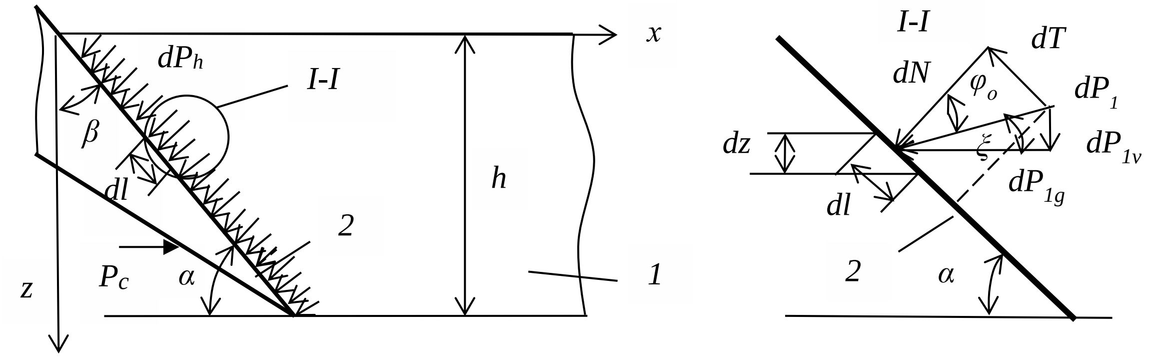


Figure 1 - Calculation scheme for cutting homogeneous soil: *1* - soil, *2* – cutting element, *α* – cutting angle, *β* – angle of inclination of the cutting element surface, *h* – cutting depth, $P_c$ – ground cutting force, $dP_h$ – elementary forces of ground resistance to cutting, *dl* – elementary length of the cutting element, *dN* - normal component, *dT* – tangent component, $dP_{1g}$ - tangent to the cutting path (horizontal), $dP_{1v}$ - normal to the cutting path (vertical), $\varphi_o$ – the angle of deviation of the resultant from the normal component *dN*

The cutting force of the ground, at the time of the onset of the limit equilibrium state, is balanced by the force of the ground's resistance to cutting – $P_h$ (Fig. 1):

$$P_c = P_h \ . \tag{1}$$

The elementary force of ground resistance to cutting is the projection of the resultant force $dP_1$ on the tangent to the ground cutting path (per unit of cutting width):

$$dP_{1g} = dP_1 \cos\xi \, , \ \xi = \pi/2 - (\alpha + \varphi_0), \quad \beta = \pi/2 - \alpha \, . \tag{2}$$

The normal component of the force to the surface of the cutting element is:

$$dN = (\sigma_n + H)dl \, . \tag{3}$$

Tangent component of the force on the surface of the cutting element:

$$dT = \tau_n dl \, , \tag{4}$$

$$dl = dz/\sin\alpha \, . \tag{5}$$

Normal, tangential limit stress on the surface of the retaining wall and dependencies for $a_{\beta i}$ are defined in [1]:

$$\sigma_n = (\gamma h + p + H)a_{\beta i} - H \, , \ \tau_n = (\sigma_n + H)\tan\varphi_0 \, . \tag{6}$$

To determine the normal force component along the entire length of the cutting element, we integrate the expression (3) taking into account the cutting depth (5):

$$N = \frac{1}{\sin\alpha}\int_0^h \sigma_n dz = \frac{a_{\beta_i}\left(0{,}5\gamma h^2 + ph + Hh\right) - Hh}{\sin\alpha} \, . \tag{7}$$

To determine the tangent component of the force along the entire length of the cutting element, it is necessary to integrate the expression (4) taking into account (5) for the cutting depth *h*:

$$T = \frac{1}{\sin\alpha}\int_0^h \tau_n dz = \frac{\left[a_{\beta_i}\left(0{,}5\gamma h^2 + ph + Hh\right)\right]\tan\varphi_0}{\sin\alpha} \, . \tag{8}$$

The resultant force of ground resistance to cutting, taking into account the cutting width – *b*, is determined by the dependence:

$$P_1 = \sqrt{N^2 + T^2} \cdot b = \sqrt{\left(A - Hh/\sin\alpha\right)^2 + \left(A\tan\varphi_0\right)^2} \cdot b \, , \tag{9}$$

where $A=\frac{a_{\beta i}\left(0{,}5\gamma h^2+ph+Hh\right)}{\sin\alpha}$.

The tangent force of resistance to the cutting path (horizontal component) is equal to:

$$P_{g_1}=P_1\sin(\alpha+\varphi_0). \qquad (10)$$

The normal resistance force to the cutting path (vertical component) is:

$$P_{v_1}=P_1\cos(\alpha+\varphi_0). \qquad (11)$$

Thus, the strength of resistance of a homogeneous ground to cutting with a sharp cutting tool, in a steady-state mode, with a two-dimensional measurement is determined by the formula:

$$P_{ch}=\sqrt{\left(A-\frac{Hh}{\sin\alpha}\right)^2+\left(A\tan\varphi_0\right)^2}\,\sin\left(\alpha+\varphi_0\right)\cdot b\ , \qquad (12)$$

where $A=\frac{a_{\beta i}\left(0{,}5\gamma h^2+ph+Hh\right)}{\sin\alpha}$.

The analysis of formula (12) shows that the resistance force of a homogeneous soil depends on: adhesion, volume weight, internal friction angle, ground friction angle on the surface of the cutting element, cutting geometry: angle, depth, cutting width and loading on the ground surface.

The maximum value of the total cutting force depends in a straight line on the volume of the soil in the limit equilibrium state (Fig. 2). It is based on the scheme [18], [19].

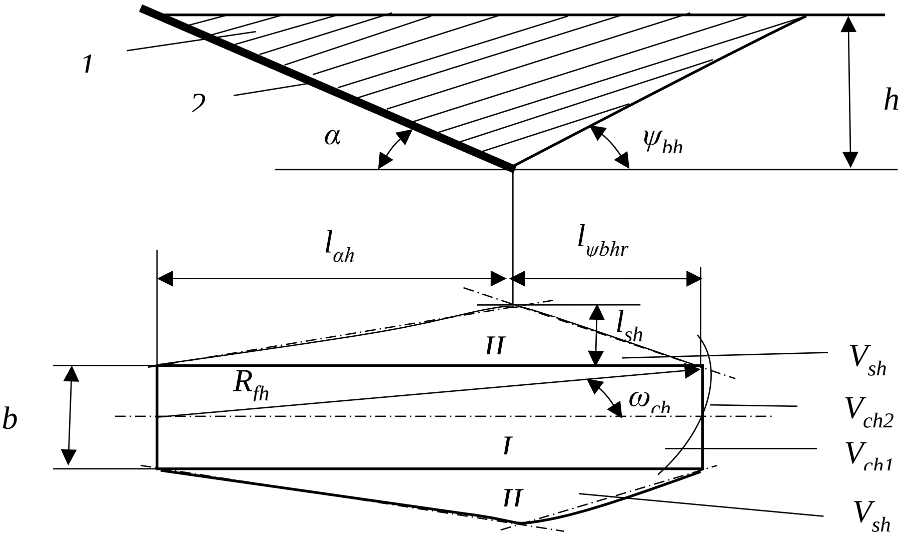


Figure 2 - Diagram of the ground cut during blocked cutting: *I* - Central wedge, *II* - side sickle, $R_{fh}$ - radius of the central wedge, $l_{sh}$ - side distance

The resistance force of the Central wedge to cutting is determined by the formula (12), and the lateral resistance forces are expressed in terms of the volumes of sickle soils in extreme equilibrium by means of the spatiality coefficient $\eta_{np}$:

$$\eta_{sp}=\begin{cases}1, \text{ two-dimensional difference,}\\ 1+\frac{n_s V_{sh}}{V_{ch}}, \text{three-dimensional difference}\end{cases}, \qquad (13)$$

where $V_{ch}$ is the amount of soil of the Central wedge, $V_{sh}$ – volume of soil lateral sickle, $n_s = 0$, with the free cutting, $n_s = 1$, when polubarinova cutting, $n_s = 2$, at locked cuts.

The total maximum cutting force is determined by the expression:

$$P_h=\eta_{sp}P_{ch}\ . \qquad (14)$$

Analytical expressions for determining the volumes of soil that are in marginal equilibrium further allow the calculation of the specific energy intensity and the cost of a unit of soil development analytically. The volume of the soil of the central wedge is determined by the dependence:

$$V_{ch} = V_{ch_1} + V_{ch_2} = 0.5hR_{fh}\left(b\cos\omega_{ch} + 0.5R_{fh}(2\omega_{ch} - \sin 2\,\omega_{ch})\right). \quad (15)$$

$$R_{fh} = \sqrt{\left(h\left(\cot(\alpha) + \cot(\psi_{bh})\right)\right)^2 + (b/2)^2},$$
$$\omega_{ch} = a\sin(b/2)/R_{fh}. \quad (16)$$

In [1], the value of the angle ψ0 is defined as: $\psi_o = \pi/4 - \varphi/2$. The volume of the soil of the lateral sickle is determined by the dependence (Fig. 2):

$$V_{sh} = hR_{fh}\cos\omega_{ch} l_{sh}/6 \quad (17)$$

The total volume of destroyed homogeneous soil is determined by the expression:

$$V_h = 0.5hR_{fh}\left(b\cos\omega_{ch} + 0.5R_{fh}(2\omega_{ch} - \sin 2\,\omega_{ch})\right) + n_s\, hR_{fh}\cos\omega_{ch}\, l_{sh}/6 \quad (18)$$

According to the results of the central composite rotatable experiment, a regression model of the lateral distance of the sickle ($h = 0.15$ m) ($\alpha^0$, $C_0$, hit, $b$, m) [23-26]:

$$l_{sh} = 0.2354 - 0.0078\alpha + 0.0015C_0 - 0.1896b + 0.0001\alpha^2 + 0.00022C_0^2 + 0.1607b^2 - 0.00003\alpha C_0 + 0.0049\alpha b - 0.0035C_0 b \quad (19)$$

Experimental work on cutting loam, semi-blocked cutting [27] (table 1) was carried out.

Table 1 - Parameters of loam and its cutting

| $\gamma$, $N$/m$^3$ | $C$, $N$/m$^2$ | $\varphi,^o$ | $\varphi_{0},^o$ | $b$, m | $h$, m | $\eta_{sp}$ | $\alpha,^0$ | $V_{sr}$, m/c | $\psi_{bh},^0$ | $P_{he}$, $N$ | $P_h$, $N$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 20010 | 26000 | 31 | 23 | 0.2 | 0.15 | 1.202 | 45 | 0.1 | 29.5 | 2974 | 2794.2 |

**It was taken results**. The relative discrepancy between the experimental ($P_{he}$) and theoretical resistance forces ($P_h$) is 6.05%.

We perform a computational analysis of the resistance forces predicted by two-dimensional models [2,3,4,5,18,19], based on the data in table 1, with a loading $q = 5000$ $N$/m$^2$. The analysis shows good convergence between the models Yu. Vetrov, K. Artemyev and the authors (0.6...13.1%), and satisfactory convergence between the McKyes, E. and O. S. Ali model ($\psi_0 = 37^0$, which provides a minimum value of coefficients) (25.8%), and the B. Balovnev model gives an overestimated value of ground resistance to cutting (60.2%).

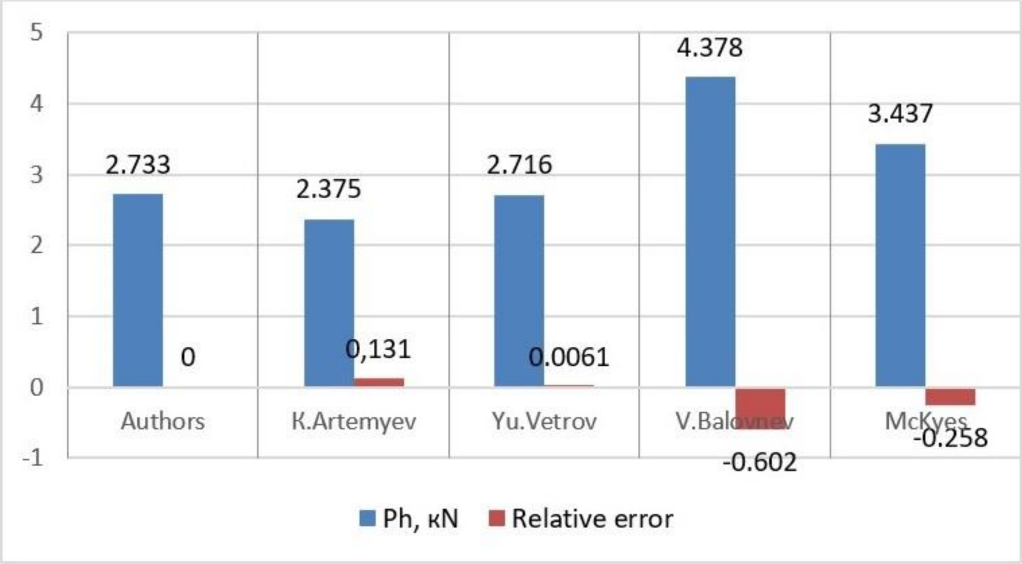


Figure 3 - Comparative computational analysis of ground resistance forces to cutting using two-dimensional models

The results of a comparative analysis between the three-dimensional models of the authors and McKyes (1985), J. V. Perumpral (1983) without loading according to table 1 are shown in Fig.4.

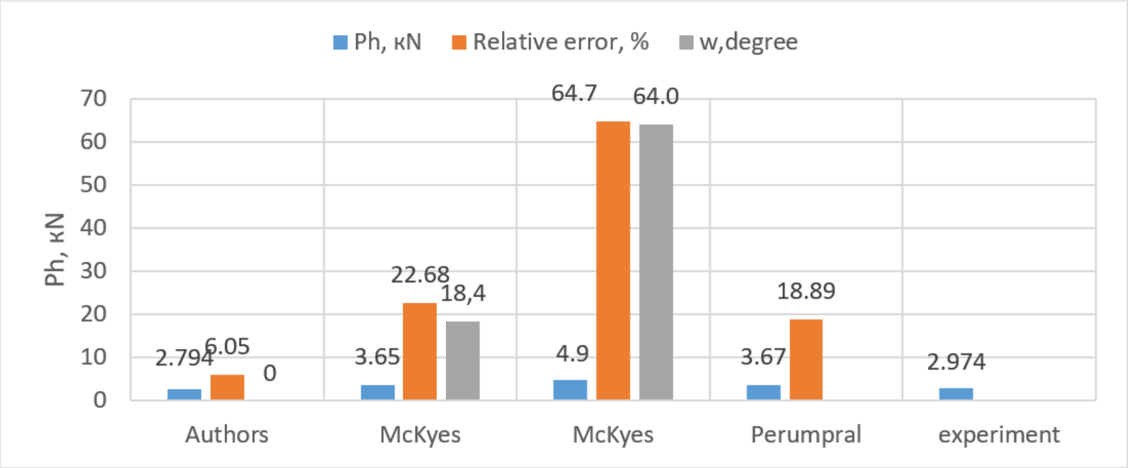


Figure 4 - Comparative analysis between three-dimensional models

In [17] it is indicated that the value of the angle ω in the McKays model (1985) is overestimated. If we assume ω = 18.40, then based on the result of the multiple regression model (19), the relative error between the models of the authors and McKays (1985) is reduced to 22.68%. The value of the angle of deviation of the lateral sickle ω according to the mckies model (1985) is overestimated in comparison with experimental data (Table 1-Table 4). The relative error between the models of the authors and J. V. Perumpral, R. D. Grisso, C. S. Desai. (1983) - 18.89% (Table 4).

Table 2 - Volume parameters of the soil

| $l_{sh}$, m | $n_s$ | $R_{fh}$, m | $\omega_{ch}$, $^o$ | $V_{ch}$, $m^3$ | $V_{sh}$, $m^3$ | $V_h$, $m^3$ | $\eta_{sp}$ | $P_{ch}$, N | $P_h$, N |
|---|---|---|---|---|---|---|---|---|---|
| 0.124 | 1.0 | 0.42699 | 13.55 | 0.006346 | 0.001287 | 0.007633 | 1.202 | 2324.6 | 2794.2 |

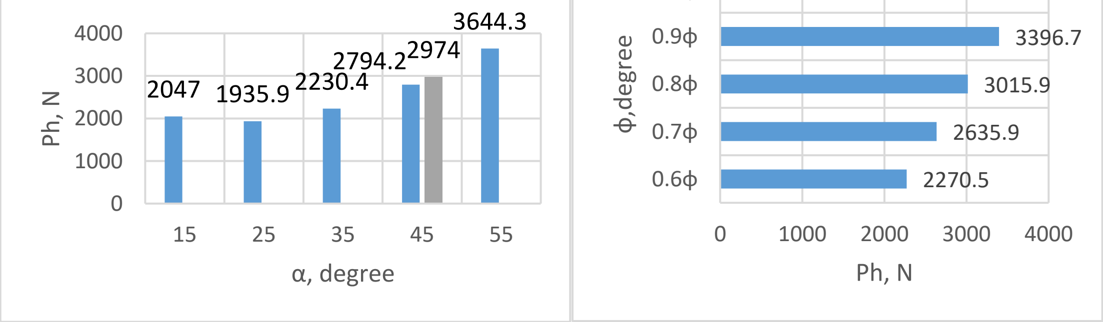
Table 3 – Results of calculation by the model of Mackiesa - Ali

| W, N | Q, N | P, N | $P_1$, N | $P_o$, N | $N\gamma$ | Nc | Nq | Na | F, N | ω, $^o$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 5034.9 | 0 | 2970.8 | 1929.6 | 4900.4 | 1.5605 | 2.041 | 3.121 | 0.8434 | 2970.8 | 64.02 |
| 5034.9 | 0 | 2970.8 | 677.6 | 3648.4 | 1.5605 | 2.041 | 3.121 | 0.8434 | 2970.8 | 18.4 |

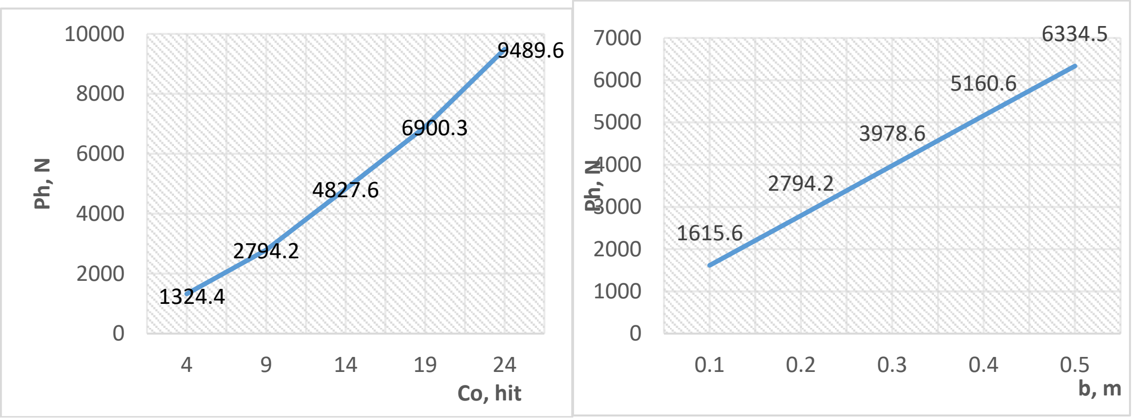
Table 4 - Calculation Results based on the model of J. V. Perumpral, R. D. Grisso, C. S. Desai

| ADF, N | $CF_1$, N | $CF_2$, N | $SF_2$, N | $A_d$, N/$m^2$ | R, N | $K_o$ | Z, m | A, $m^2$ | W, N | P, N |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.02121 | 1584 | 809.49 | 9.077 | 1.0 | 15.1065 | 0.48496 | 0.05 | 0.0311 | 124.6 | 3666.6 |

Further, a computational analysis of the dependence of the predicted cutting resistance force without overload on the cutting angle, the angle of ground friction on the surface of the cutting element, and the depth and width of the cutting (Fig.5 *a,b,c,d*).



*a)* *b)*



*c)* *d)*

Figure 5 - Dependences of the cutting resistance force: *a)* – on the cutting angle, *b)* - on the angle of ground friction on the surface of the cutting element, *c)* - on the number of strokes, *d)* - on the cutting width.

**Conclusions and prospects of applying the methodology**. The analysis of the dependencies shows that the optimal cutting angle should be $25^0$ ... $30^0$, which provides a minimum cutting resistance force, an increase in the angle of external friction is accompanied by an increase in the ground resistance force to cutting. The relationship between the resistance force and the cutting depth is non-linear, and the relationship between the resistance force and the cutting width is a linear.

The accuracy of predicting the cutting resistance force is positively affected by taking into account the shape of the fracture plane and the use of the results of field and laboratory tests of soils and automatic identification of parameters of strength properties of soils in the model increases the practical applicability of the research results.

It is noted that the above methodology for calculating the resistance force of homogeneous soil is used to determine the strength of resistance to destruction of soil containing stony fractions in subsequent studies of the authors.

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## БІРТЕКТІ ТОПЫРАҚТЫҢ КЕСУГЕ ТӨЗІМДІЛІК КҮШІН БОЛЖАУ

**Аннотация:** топырақтың бұзылу жазықтығының конфигурациясын ескере отырып, борпылдақ ортаның шекті тепе-теңдік теориясы негізінде топырақтың кесуге қарсы тұру Күшін болжау моделі жасалды. Топырақтың жойылуының үш өлшемді сипаты кеңістік коэффициентімен бағаланады. Модельде топырақ беріктігінің параметрлерін автоматты түрде анықтау нәтижелері және топырақтың далалық және зертханалық зерттеулерінің деректері қолданылады. Барлық модельдерде қарсылық күші функционалды түрде максималды кернеу күйіндегі топырақтың көлеміне байланысты болады. Орталық сына мен бүйір орақтың топырақ көлемінің аналитикалық өрнектері алынды, бұл Топырақты кесу процесінің нақты энергия сыйымдылығын аналитикалық есептеуге мүмкіндік береді. Әзірленген модельдің дұрыстығы шекті тепе-теңдік, жер жұмыстарының іргелі теңдеуі және эксперименттік мәліметтер негізінде алынған модельдермен салыстырғанда бағаланады. Қарсыласу күшінің Топырақты кесу режимдеріне тәуелділігі анықталды.

**Түйін сөздер:** қарсылық күшінің болжамы, жер қазу жұмыстарының іргелі теңдеуі, борпылдақ ортаның шекті тепе-теңдігі, қарсылықтың топырақ көлеміне тәуелділігі, кеңістіктік коэффициент, бұзылудың үш өлшемді сипаты, балғаның жағы, орталық сына, шекті тепе-теңдіктегі топырақ көлемі.

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## ПРОГНОЗИРОВАНИЕ СИЛЫ СОПРОТИВЛЕНИЯ ОДНОРОДНОГО ГРУНТА РЕЗАНИЮ

**Аннотация:** разработана модель прогнозирования силы сопротивления грунта резанию на базе теории предельного равновесия сыпучей среды, учитывающая конфигурацию плоскости разрушения грунта. Трехмерный характер разрушения грунта оценивается посредством коэффициента пространственности. Модель использует результаты автоматической идентификации прочностных параметров грунта и данные полевых и лабораторных испытаний грунтов. Во всех моделях сила сопротивления функционально зависит от объема грунта, находящегося в предельном напряженном состоянии. Получены аналитические выражения объема грунтов центрального клина и бокового серпа, которые позволяют аналитически рассчитать удельную энергоемкость процесса резания грунта. Оценена корректность разработанной модели в сравнении с моделями, полученными на основе предельного равновесия, фундаментального уравнения землеройных работ и с экспериментальными данными. Установлены зависимости силы сопротивления от режимов резания грунтов.

**Ключевые слова:** прогнозирование силы сопротивления, фундаментальное уравнение землеройных работ, предельное равновесие сыпучей среды, зависимость силы сопротивления от объема грунта, коэффициент пространственности, трехмерный характер разрушения, боковой серп, центральный клин, объем грунта, находящегося в предельном равновесии.

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