NOVAS ESPECIFICAÇÕES DA TEORIA DE CORTE DO SOLO

NEW SPECIFICATIONS OF THE THEORY OF GROUND CUTTING

НОВЫЕ ПОЛОЖЕНИЯ ТЕОРИИ РЕЗАНИЯ ГРУНТОВ

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RESUMO

A terraplanagem é realizada por uma diversidade de máquinas de escavação: escavadeiras, raspadores, motoniveladoras, escavadeiras de dragagem, máquinas de escavação, instalações de perfuração, etc. Um número de pesquisadores estavam envolvidos no corte do solo e em geral, a teoria de corte do solo é bastante desenvolvida. Entretanto, suas disposições estão corretas para a determinação de máquinas do solo realizando cortes quase retilíneos próximos a uma superfície, em meio desidratado. Como mostra a prática, as disposições conhecidas da teoria do corte não permitem calcular a precisão do modo e carregamento dessas máquinas. Este artigo é dedicado ao estabelecimento das regularidades que determinam a resistência do solo à destruição por máquinas de perfuração e fresamento de construção. As dependências determinadas que determinam a lei da modificação de uma esquina de uma pastilha cortando o solo em uma função do acoplamento, pressão no solo, pressão hidrostática e hidrodinâmica em uma superfície, o ângulo do corte, os ângulos de fricção interna e externa são determinados. Coeficientes de condições de trabalho que descrevem um quadro de alta qualidade do corte do solo são recebidos e dão uma razão de forças em caso de destruição retilínea do solo às forças que surgem no caso de sua moagem.

Palavras-chave: *corte de solo, resistência, força, coeficientes, corpo de trabalho, máquinas de escavação.*

ABSTRACT

Earthwork is performed by some digging machines: excavators, scrapers, graders, dragline excavators, ditching machines, boring installations, etc. Some researchers were engaged in the cutting of soil, and in general, the theory of cutting of soil is rather developed. However, its provisions are correct to the determination of machines of the soil performing almost rectilinear cutting close to a surface, in a dehydrated medium. As practice shows, the known provisions of the theory of cutting do not allow to calculate accuracy the mode and loading of these machines. This article is devoted to the establishment of the regularities determining soil resistance to destruction for construction boring and milling machines. The determined dependences determining the law of change of a corner of a chip when cutting soil as a function from the coupling, pressure in soil, hydrostatic and hydrodynamic pressure upon a surface, the angle of cutting, the angles of internal and external friction are determined. Coefficients of working conditions which describe a high-quality picture of cutting of soil are received and give a ratio of forces in case of rectilinear destruction of soil to forces arising in case of its milling.

Keywords: *cutting of soil, resistance bearing, force, coefficients, working body, digging machines.*

АННОТАЦИЯ

Земляные работы выполняются рядом землеройных машин: экскаваторы, скреперы, грейдеры, экскаваторы-драглайны, канавокопательные машины, буровые установки и т.д. Ряд исследователей

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занимался резкой грунта, и в целом теория резания грунта достаточно развита. Однако, его положения верны для определения машин почвы, выполняющих практически прямолинейную резку вблизи дневной поверхности, в обезвоженной среде. Как показывает практика, известные положения теории резки не позволяют рассчитывать точность режима и нагрузки этих станков. В связи с этим данная статья посвящена установлению закономерностей, определяющих устойчивость грунта к разрушению для строительно-расточных и фрезерных станков. Установлены зависимости, определяющие закон изменения угла стружки при резке грунта как функции от сцепления, давления в грунте, гидростатического и гидродинамического давления на поверхность, угла резания, углов внутреннего и внешнего трения. Получены коэффициенты условий труда, которые описывают качественную картину вырезывания грунта и дают соотношение сил при прямолинейном разрушении грунта к силам, возникающим при его фрезеровании.

Ключевые слова: *резка грунта, щепка, контактная нагрузка, сила, коэффициенты, рабочий орган*

INTRODUCTION

In the Republic of Kazakhstan, huge amounts of earthwork are carried out. It concerns both the mining industry and also construction. Development of soil and rocks is the main transaction of engineering procedure of a bases construction. At the same time, by resource intensity this transaction exceeds others. Digging machines are the leading link of engineering procedure of construction. Some digging machines, for example, milling and boring, have working bodies of small diameter, work deeply from the surface of the soil, in the environment of clay solution or water (Baimakhan *et al.*, 2008; Mendekeev and Turgunbaev, 2016; Mendekeev and Turgunbaev, 2015; Mendekeev and Turgunbaev, 2017). These working conditions are characteristic of construction of underground constructions by method "wall in soil" and the device of bored piles. As practice shows the known provisions of the theory of cutting do not allow to calculate with sufficient degree accuracy the mode and loading of these machines (Baimakhan *et al.*, 2016). Therefore, the problem of determination of drag forces of machines cutting working at big depths in the environment of liquid and with small curvature of movement of the working body is urgent (Turgunbaev, 2017; Mikheev, 2016; Alyabyev and Kalinin, 2016).

The theory of ground cutting is the section of mechanics of grounds devoted to ground destruction by separating shaving from the ground massif. The theory of ground cutting is rather well developed for calculation of parameters of the digging cars working at small depths (up to 15 m), in the conditions of "dry" face, at movement trajectories of cutting tools close to rectilinear. Its provisions are correct when calculating loading of excavators, graders, bulldozers and other similar cars (Abukhanov, 2006; Kochetkova, 2012; Khaibullin, 1989). However so far the regularities considering influence on force of cutting depth, face, curvature of movement trajectory of cutting tools, hydrodynamic and hydrostatic pressure upon the face when destructing the ground under a layer of clay solution or in water), degrees of a filtration of bottom-hole liquid into the ground aren't defined in it. There is the whole class of machines which the listed conditions characterize operation. These are the milling and boring cars used at construction by way of "a wall in a ground" and the device of bored piles. The especially difficult process is ground milling when going through narrow and deep trenches in the environment of the clay thixotropic solution necessary for preventing the walls of a trench from destruction (Lukashuk *et al.*, 2018; Petrochenko, 2018; Vakhidov *et al.*, 2014; Sokolov, 2018a; Sokolov, 2018b; Sokolov, 2018c; Sokolov *et al.*, 2017; Sokolov and Ryabinov, 2015).

MATERIALS AND METHODS

For setting resistance forces to milling, we will solve the following problems in the methodical sequence:

1. Let's sort out the value of the cutting force relations by the known techniques (in the dry face, with a small depth of the face (H<10m)) to cutting force taking into account the listed features.

2. Let's determine specific forces of giving and rotation of a mill on the face considering the experimental and theoretical results.

3. Let's confirm the received dependences experimentally.

Let's consider the balance of an element of the cut-off shaving in the period, preceding the chip. In a shaving element with the speed of a sound, the shock wave of tension leading to the destruction of the ground extends. The front of the deformation wave deviates from the normal one to the front side of the cutting tool on the friction angle μ. The tension of elastic deformation causes volume deformation of the ground in coherent molecular grounds which we consider there are also plastic deformations. These deformations are characterized by a change of shaping and emergence of a core of consolidation in front of the cutting tool. After formation of a core and energy accumulation of elastic deformations (Abukhanov, 2006; Yoshida *et al.*, 2013; Ustinov and Shchipunov, 2014) overcomings force of adhesion of the ground on the so-called platform of a chip occurs (the line a-b in Figure 1).

RESULTS AND DISCUSSION:

The element of the chopped-off shaving (ABC) is affected by force of the normal pressure N_p, geostatic pressure P_σ, hydrostatic $P_{h.s.}$ and hydrodynamic pressure $P_{h.d.}$, shaving P weight, the centrifugal force of $P_{c.f.}$, arising because of curvilinearity of the movement of the cutting tool, normal and tangent reactions from the ground at the area of the chip of R^E and R^n. The small radius of the trajectory of the movement of the cutting tool increases the friction of the rear side of the cutting tool to the ground on which there are ground resistance forces R^τ_{cm} and R^δ_{cm}. The rear side of the cutting tool is affected by forces of hydrostatic and hydrodynamic pressure. Forces which accounting at the description and chip of the ground element, we consider for the first time in the figure are noted by a star (*).

We consider what the liquid environment in the face (solution, water) was filtered for the value hf. The thickness of the cut makes h, and it consists of the thickness of the cut of hp and collapse hcm. The platform of the chip is tilted to the tangent to the cutting trajectory at the angle ψ. The cutting tool has b width, the angle of cutting δ, rear angle ν, the width of the wear platform a. The trajectory of the movement of the cutting tool is tilted to the horizontal at the angle β (Shepel and Sychev, 2014; Shepel, 2015; Kravets and Stonio, 2016).

According to the scheme in Figure 1, the weight of the element of the cut-off shaving and centrifugal force are defined by expressions (Equations 1, 2), where r – the radius of trajectory curvature of the cutting tool movement. Milling and boring cars work at big depths. By the existing techniques force of ground, cutting is determined without taking into account its change by depth (Nelozerov and Savekiev, 2010; Janosevic *et al.*, 2012; Babich, 2016). Meanwhile, with an increase in depth the geostatic household pressure of liquid increases in the ground. The Soviet scientist N.M. Gersevanov (Gotman and Glazachev, 2014) proved the principle of the hydro capacity of the ground. Use of the principle of hydro capacity gives the chance to resolve the issues connected with the change of tension of the condition of the ground skeleton.

At a depth of Z the ground element (Figure 2) is affected by the main tensions:

$$\sigma_1 = \rho_2 Zy,\ \sigma_2 = \rho_2 Zy\theta,$$

where θ – coefficient of the side spreader of the ground skeleton.

When discharging the ground of the communications with the massif, pressure, and spreader are eliminated, however, the content of water in pores, and therefore the coefficient of porosity does not change. In this period the ground element is under comprehensive internal pressure σσ, arising owing to aspiration of the destroyed ground sample to expansion. Proceeding from the research (Gotman and Glazachev, 2014), it is fair (Equation 3), where γ3 – the specific weight of ground particles; ε – porosity coefficient.

The accounting of the internal pressure through the coefficient of the side spreader is complicated by the complexity of its definition. It is more convenient to determine this size through the coefficient of cross deformation of ground Kc, (Equation 4) then (Equation 5), or having designated (Equation 6), we obtain $\sigma_\sigma = \theta_n Z \rho_2 q$. The coefficient of cross deformation of the ground Kc can accept values only ranging from 0 to 0,5. The values are impossible as in this case, the sign of volume deformation would change, that is when compression there would be the expansion of the body. For example, for clays, the coefficient of cross deformation is equal to 0,17.

The tangent tension of shift increases at the increase of depth of cutting due to an increase of the internal pressure of the ground, also resistance to the shaving separation increases. Therefore (Equation 7), where τ_1 – tangent tension to shift on the day surface. The element of the cut-off shaving is affected by the hydrostatic pressure of the liquid (Figure 2, the line bc). The area of pressure of F_p – Equation (8).

When the movement of liquid in the face under the influence of rotation of the mill pressure put upon the face will be defined by the hydrostatic pressure of a column of liquid and hydrodynamic pressure created by rotation of the mill, according to the Bernoulli law, the force operating on the face P_{zh} will be defined by the expression (Boldirev and Malyshev, 2009; Kadyrov and Haibullin, 2007) (Equation 9).

Dependence allows considering both the hydrostatic and hydrodynamic pressure upon the face. When using the formula (9) in practical calculations, it is necessary to multiply the second addend of the right part on the coefficient considering the form of the moving element. In the process of milling the layer-by-layer removal of the ground from the face (on the thickness of the cut-off shaving) occurs. If work happens at the bottom of a reservoir, the ground is, as a rule, filtered by water on all depth of the face. In this case, the cutting tool is affected by the volume hydrostatic and hydrodynamic pressure changing cutting force. At the same time physical and mechanical properties of the ground change, including the angles of external and internal friction, the chip angle, etc. This process is rather investigated by Nedorezov I. A., Turgumbayev Zh., Ogorodnikov S. P. (Nedorezov and Savekiev, 2010; Gotman and Glazachev, 2014). If filtration depth for one turn of rotation of the mill is insignificant, then the total pressure of liquid upon the area of S is overcome. With a depth of filtration of h_f the shaving exceeding thickness, the process is similar to cutting in completely filtered (water-saturated) grounds. These two options are a boundary.

Shatalov A. A. assumed that force of P_{hs} depends on the coefficient of pressure transmission. The value of this coefficient reaches the greatest values in grounds with the smallest permeability and the smallest values in the poor bound sands. The physical sense of the coefficient was displayed by Kadyrov A.S., who offered that its value is always less or is equal to one and it is the more, the more liquid filtration speed value in the ground – V_f and the less, the less the considerable speed of giving the working body to the face v (Equation 10), where η – coefficient of drive of pressure (Equation 11)

Increasing η the ratio of values of the thickness of filtration shaving h_f and cutting h_p increases, and the area of the sinking of the cutting tool through hydrostatic pressure through the face decreases. Geometrically the line *a-b* is replaced by the b'-c' line (Figure 1). The filtration speed is determined according to the Darci law, having the representation (Equation 12), where K_f – the filtration coefficient fluctuating from $1 \cdot 10^{-7}$ m/s for clays and $1 \cdot 10^{-3}$ m/s for the grave and sandy grounds; J – piezometric pressure. The filtration speed is measured by the volume of the liquid passing through a unit of area. The piezometric pressure is a hydraulic gradient equal to the difference in pressures per unit length of the filtrational line. The pressure on the face which is at Z depth, being according to the Bernoulli law is equal (Equation 13). The hydraulic line was defined as a half of a circle (for milling the face), then piezometric pressure (Equation 14), where $Z_1=0$ – initial ordinate of driving; $L_0=0$ – circle length at the beginning of the turn.

Taking into account the received dependence, piezometric pressure was determined in Equation (15). The received expression differs from the formula (12) and considers geometrical mill parameters and speed of ground cutting. Taking into account the value η and dependence (11) the liquid pressure upon the face is defined with by dependence (Equation 16). The influence of P_l value on tangent resistance to shifting is equal (Equation 17). In Figure 1 shear zones and ground cutting are shown. Shear occurs on the area of wear of a cutting tool when milling the area, the shear increases because the force of cutting deviates the tangent to the trajectory of the movement at the angle β_{fr}. This angle arises as a result of the addition of absolute and figurative speeds of the movement of a mill. Values of this angle from 2^0 to 4^0 aren't important when calculating forces of cutting by a sharp knife, but considerably influence the formation of the shear platform. The relation of the shear areas and cutting (1) will be defined by the following dependence (Equation 18), where h_u – height of the platform of wear; K_{sh} – coefficient a ground smyatiya.

The resistance of the ground shear considerably exceeds the resistance when cutting. In this regard, we offer to consider an increase in the force of cutting because of ground shear, coefficients K_ω. The offered coefficient K_ω depends on the radius of the trajectory of the movement of the cutting tool, and it is the more, the more the radius as the shear area of the ground due to the reduction of the volume of the face increases is less. This assumption has to be checked experimentally.

The received dependences allowed to define the cutting force formula as the sums of cutting forces on "dry" additional forces of cutting from geostatic, hydrostatic and hydrodynamic pressure. The coefficients of working conditions representing the relation of additional force of cutting to cutting force on "dry" and on a day surface were defined for this purpose (Equations 19-22), where K_δ, K_c, K_p and K_c – respectively coefficients of working conditions taking into account the geostatic pressure (K_δ); hydrostatic and hydrodynamic pressure (K_c); curvature of the trajectory of the cutting tool movement (K_ω); the weight of shaving (K_p) and the centrifugal force operating on shaving of K_c.

The value unit in formulas (19, 20, 21) considers cutting force in usual conditions. When taking into account of increment of cutting force, it is necessary to subtract a unit. The values of centrifugal forces and the weight of shaving are small (by calculations no more than 1%), and while carrying out the experiment, they entered a systematic mistake. Due to it, it is fair in Equation 22, where N_p^{Σ} - the total cutting force. After substitution of the values K_ω, K_c, K_δ it is received (Equation 24), where α_z – the coefficient considering the joint influence of geostatic and hydrodynamic pressure. It is more convenient to consider the value of coefficient K_ω as cutting force multiplication factor as it isn't connected with driving depth. Besides, it is difficult defined theoretically and established by us experimentally. In this regard, we received Equation 25. Proceeding from the analysis of the value of coefficient αz it follows that forces of geostatic and hydrostatic components of cutting force by depth grow up, and hydrodynamic force remains unchanged.

In case of impossibility to determine the value of coefficient K_ω experimentally its value is equal to one in dependence, and the formula is added with $h_{cm}/(1- h_c)Z$.

The coefficient K_ω is specified in the expression as a factor, for the purpose of convenience of polynomial grouping on Z depth. The coefficient has a representation (Equation 26). The following investigation phase was the establishment of settlement formulas of forces of ground destruction. The received early dependences allow to define a ratio of various components of cutting forces. But т provides very inexact results (Vetrov, 1971). For receiving more exact settlement formulas specific forces of resistance to cutting on the front side of the cutting tool of m_{free} and the side of the cutting tool m_{side} are used. These specific forces are received by the academician Vetrov Yu.A. experimentally and repeatedly checked in operation of digging cars.

In average forces and geometry, the cutting tool of a mill is affected by forces of resistance to cutting on front m_{free} and side of the cutting tool of m_{side}, resistance shear m_{sh}, and also effort of giving and torque of M. Having designed forces on the vertical axis having taken a sum moment concerning the point 0 (Figure 3) we will receive effort of giving and torque for ground milling (Equation 27), where A and B – the specific forces of resistance to giving and rotation of a mill depending on specific forces of resistance of ground destruction by side and front sides (Equations 28, 29), where λ – the coefficient considering deviation of the angle of cutting from 45^0 at values of the angle of cutting the 45^0 this coefficient is equal to one.

Specific forces A and B depend on experimental values of forces m_{free} and m_{side}, cutting radius R, the width of cutting tools b, the angle of cutting δ, numbers of cutting tools on i mill. The effort of giving Q and torque M defined through sizes A and B yield results, quite exact for the theory of cutting when cutting at small depths and in a dry face (mistake not more than 17%) (Zharnitski, 2005). Taking into account working conditions at a considerable depth and in the environment of clay solution, having used the equation (23) we will receive Equation (30). The stands which are carrying out cutting by a single cutting tool (Figure 4) a full-size mill (Figure 5) were developed for carrying out the third investigation phase.

The experiment at the CP-1 stand showed that resistance to cutting at the rotary motion of the cutting tool of working body increases in comparison with the force of cutting arising on the same cutting tool (Figure 6), moving rectilinearly. On a tray of rectilinear cutting, the cutting force was determined for the same parameters as at progress. The value of the increment depends on the radius of rotation of the working body and speed of cutting. Coefficient K_ω was determined by the size of the relations of forces of cutting at a curvilinear and in-line motion of the cutting tool.

Increase in speed of cutting leads to increase of cutting force (Figure 6, a), and the less is rotation radius, so much the more the resistance of the soil grows up for destruction. At a reduction of radius the cutting force increases, at the same time, its value decreases at the reduction of speed of cutting (Figure 6, b). The coefficient K_ω increases at the reduction of the radius of force application asymptomlessly approaching cutting force at in-line motion (Figure 7). It follows from the schedule that coefficient K_ω is necessary to be considered at rotation radiuses less than 0,3 m. Change of cutting speed insignificant influences the coefficient K_ω. At speeds v<1,4 m and radiuses R>0,3 m the cutting force can be calculated without consideration the K_ω value. However, the parameters of milling and boring cars, as a rule, don't fit into these limits.

At rotary motion, the cutting speed more considerably influences the cutting force, than at rectilinear cutting with the speed 2,5 m/s the gain made 11%, and when milling (R=0,5 m), it made 19%. Nonlinearity of dependence is defined by the constancy of value $P_{h.d}$ (Figure 8). The values of specific forces for six categories of ground are given in Table 1.

CONCLUSIONS:

The resistance to cutting by side edges of a knife doesn't change in the dependence on the trajectory of the movement. In general, the results of the experiment confirmed the analytical conclusions. Definition of the influence of hydraulic pressure of clay solution upon the cutting force was carried out at the stand of modeling of milling SMP-1. The construction of the stand represented a hermetic enclosure with the ground container. In the stand one or two horizontal mills were placed. The container filled a ground entirely or which is filled up with the sand moved on mills by the hydraulic cylinder. The pressure up to 25 MPas was created by the ground pump compensating solution escapes. The drive gear of mills was carried out by shafts from hydraulic motors.

The tense torque shaft was registered, the effort of giving pressure by strain gage which is built into the hydraulic cylinder, the container course – the sensor of motion. When experimenting the radius of milling changed, mills were made with a diameter 0,1 m, 0,2 m, 0,3 m, 0,4 m, 0,5 m. The number of cutting tools on mills varied from 4 to 24, the width of the platform of wear equaled to the width of the cutting tool and the platform of wear before the experiment had a value from 1·10-2 m to 0,25·10-2 m and was created artificially. Increase in force of cutting was fixed with the pressure 4 MPas that corresponds approximately to the driving in the trench in 10 meters.

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$$P_{c.\mathrm{b.}} = \frac{PV_p{}^2}{rg}(ctg\delta + ctg\psi); \tag{1}$$

$$P = \frac{bh^2 \rho_2 g}{2} ctg\delta + ctg\psi) \text{;} \tag{2}$$

$$\sigma_\sigma = \frac{(1+2\theta)\gamma_3}{3(1+\varepsilon)} Zg = \frac{1+2\theta}{3} Z\rho_2 \,\mathrm{g}, \tag{3}$$

$$\theta = \frac{K_n}{1-K_n}, \tag{4}$$

$$\sigma_\sigma = \frac{1+K_n}{3(1-K_n)} Z\rho_2 g \;, \tag{5}$$

$$\theta = \frac{1+K_n}{3(1-K_n)}, \tag{6}$$

$$\tau = \tau_1 + \sigma_\sigma tg\varphi, \tag{7}$$

$$S = b \cdot h \cdot (ctg\delta + ctg\psi), \tag{8}$$

$$P_{zh} = \rho_c \cdot g \cdot Z \cdot F_\partial + \rho_c \frac{V_p^2 \cdot S}{2}, \tag{9}$$

$$\eta = 1 - \frac{V_{ph}}{V} = 1 - \frac{h_{ph}}{h_{ph}}, \tag{10}$$

$$h_p = hp - h_{ph}. \tag{11}$$

$$V_f = K_f \cdot J \;, \tag{12}$$

$$H = Z + \frac{V_p^2}{2g} \tag{13}$$

$$\frac{\Delta H}{\Delta L} = \frac{Z - Z_1}{\pi R - L_0} = \frac{Z}{\pi R} + \frac{V_p^2}{2\pi Rg}, \tag{14}$$

$$V_\mathrm{f} = \frac{K_\mathrm{f} Z}{\pi R} - \frac{K_\mathrm{f} V_p^2}{2\pi Rg}. \tag{15}$$

$$P_{zh} = \eta\rho_c gZ(\mathrm{ctg}\,\delta + \mathrm{ctg}\,\psi) + \rho_c h\frac{V_p^2}{2}(ctg\delta + ctg\psi) \qquad (16)$$

$$\tau = \tau_1 + P_{gd}tg\varphi. \qquad (17)$$

$$K_{sh} = \frac{h_u}{h - h_u}, \qquad (18)$$

$$K_\delta = \frac{\tau_1 + \sigma\delta tg\varphi}{\tau_1} = 1 + \frac{\sigma\delta}{\tau_1}tg\varphi, \qquad (19)$$

$$K_c = \frac{\tau_1 + P_{gs}tg\varphi}{\tau_1} = 1 + \frac{\eta\rho_c Zgtg\varphi}{\tau_1} + \frac{\rho_c V_p^2 tg\varphi}{2\tau_1}, \qquad (20)$$

$$K_\omega = 1 + \frac{h_c}{h - h_c} = 1 + K_c,. \qquad (21)$$

$$K_p = \frac{\rho_2 gh}{\tau_1} \ \text{и} \ K_c = \frac{V_p^2\rho_2 h}{2R\tau_1}, \qquad (22)$$

$$N_p^\Sigma = N_p + N_p(K_\delta - 1) + N_p(K_c - 1) + N_p(K_\omega - 1), \qquad (23)$$

$$N_p^\Sigma = N_p K_\omega(1 + \alpha_z \mathrm{Z}), \qquad (24)$$

$$N_p^\Sigma = K_\omega(1 + \alpha_z \mathrm{Z}). \qquad (25)$$

$$\alpha_z = \frac{\theta\rho_c gtg\varphi}{\tau_1} = 1 + \frac{\eta\rho_c gtg\varphi}{2\tau_1} + \frac{\rho_c V_p^2 tg\varphi}{2\tau_1 Z}. \qquad (26)$$

$$\begin{cases} M = BhR; \\ Q = Ah, \end{cases} \qquad (27)$$

$$B = 0{,}5i\lambda bm_{free}\left(1 + a\right) + im_{lat.sh}; \qquad (28)$$

$$A = 0{,}5i\lambda bm_{free}\{\left(1 + a\right)\cos\phi_{sh} + ctg\left(\delta + \mu\right)\} + im_{lat.sh}[\cos\phi_{sh}ctg\left(\delta + \mu\right)]\sin\phi_{sh} \qquad (29)$$

$$\begin{cases} M = BK_\omega(1 + \alpha_Z Z)hR; \\ Q = AK_\omega(1 + \alpha_Z Z)h, \end{cases} \qquad (30)$$

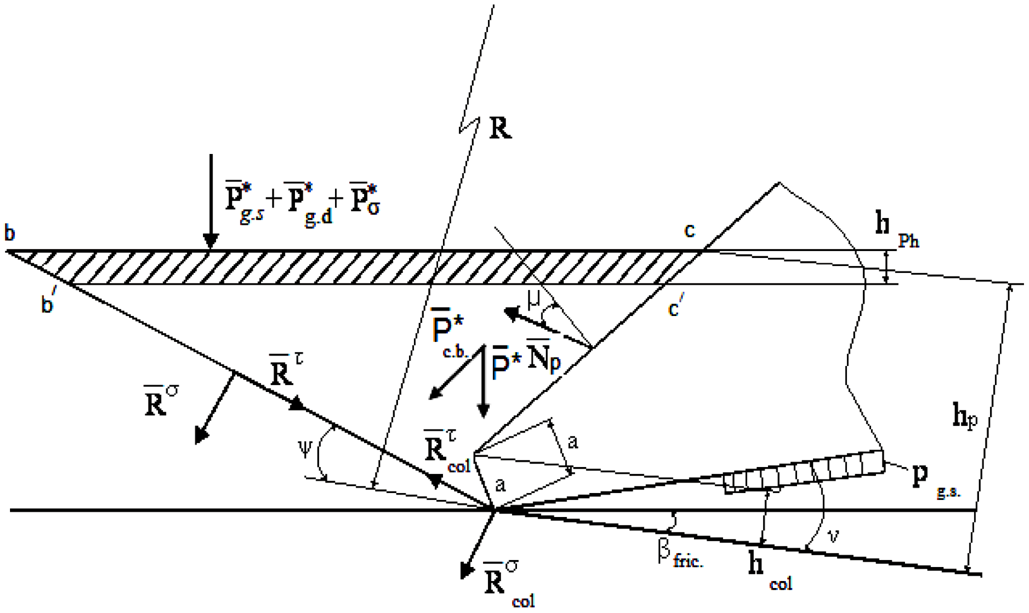


Figure 1. *The scheme of forces operating on the element of the cut-off ground shaving*

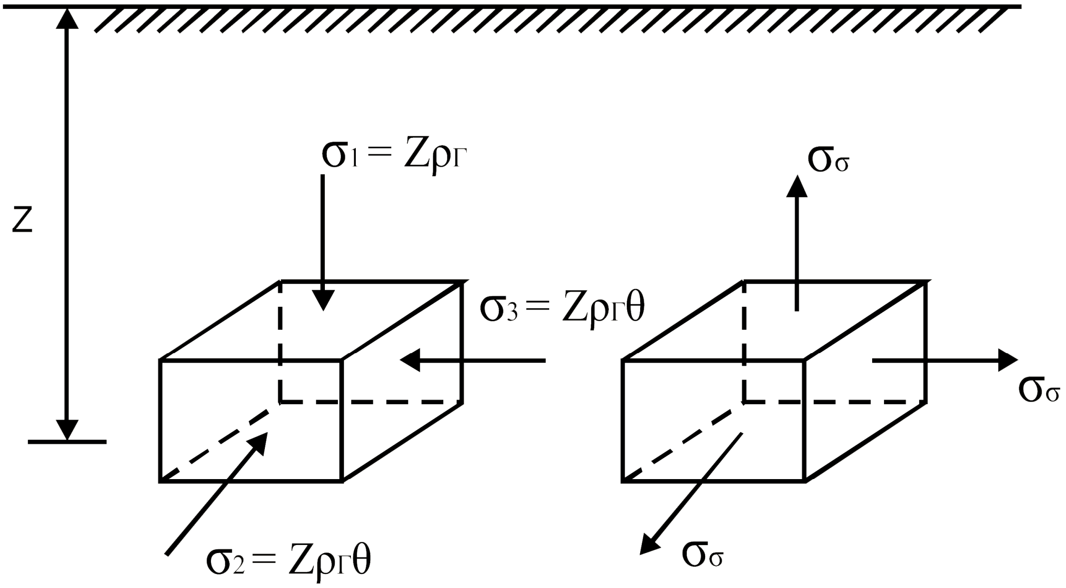


Figure 2. *The main tension in ground a – in natural bedding; b – exempted from communications*

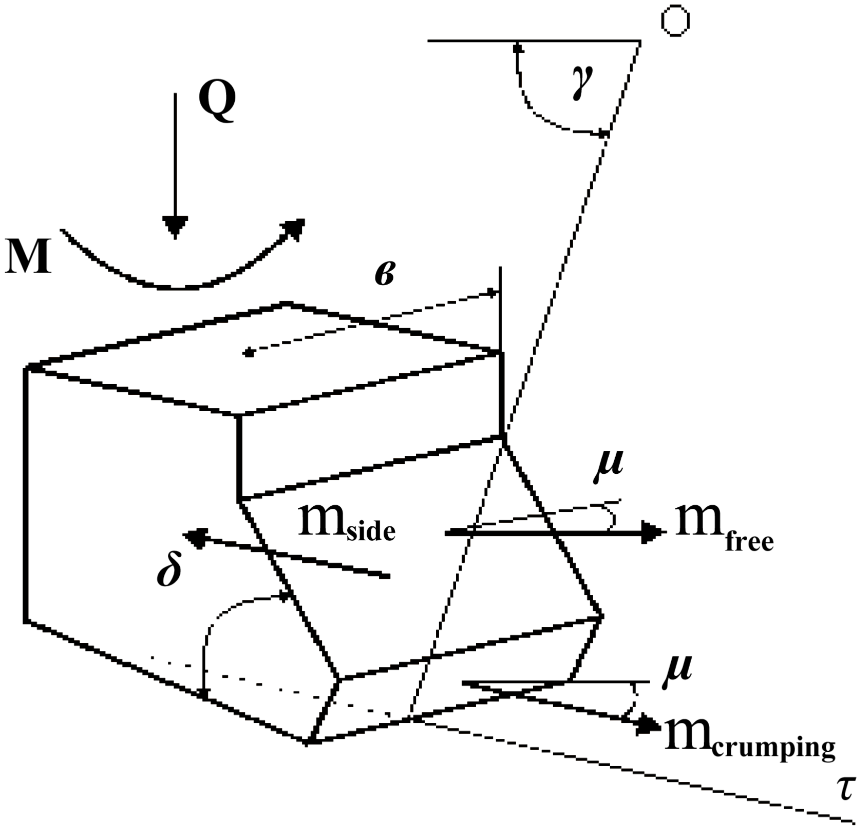
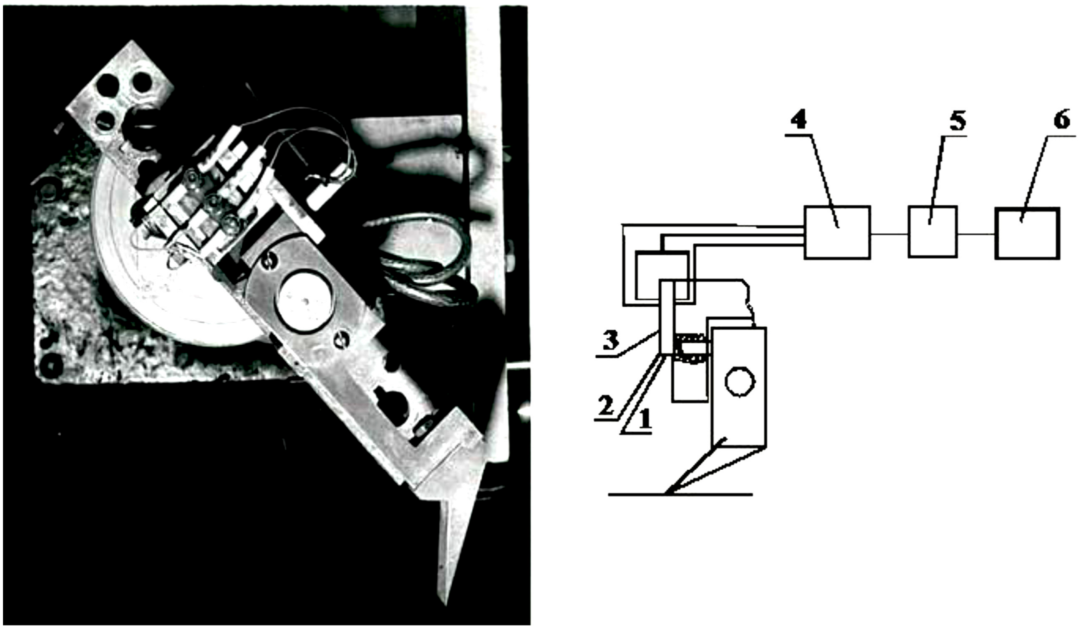


Figure 3. *The scheme of forces operating on the cutting tool of milling WP*



a *b*

Figure 4. *Tense cutter (a) and scheme of cutting tool (b) of the SR-1 stand: 1 – tense cutter; 2 – tense gages; 3 – tense booster; 4 – oscillograph; 5 – power supply unit; rectifier*

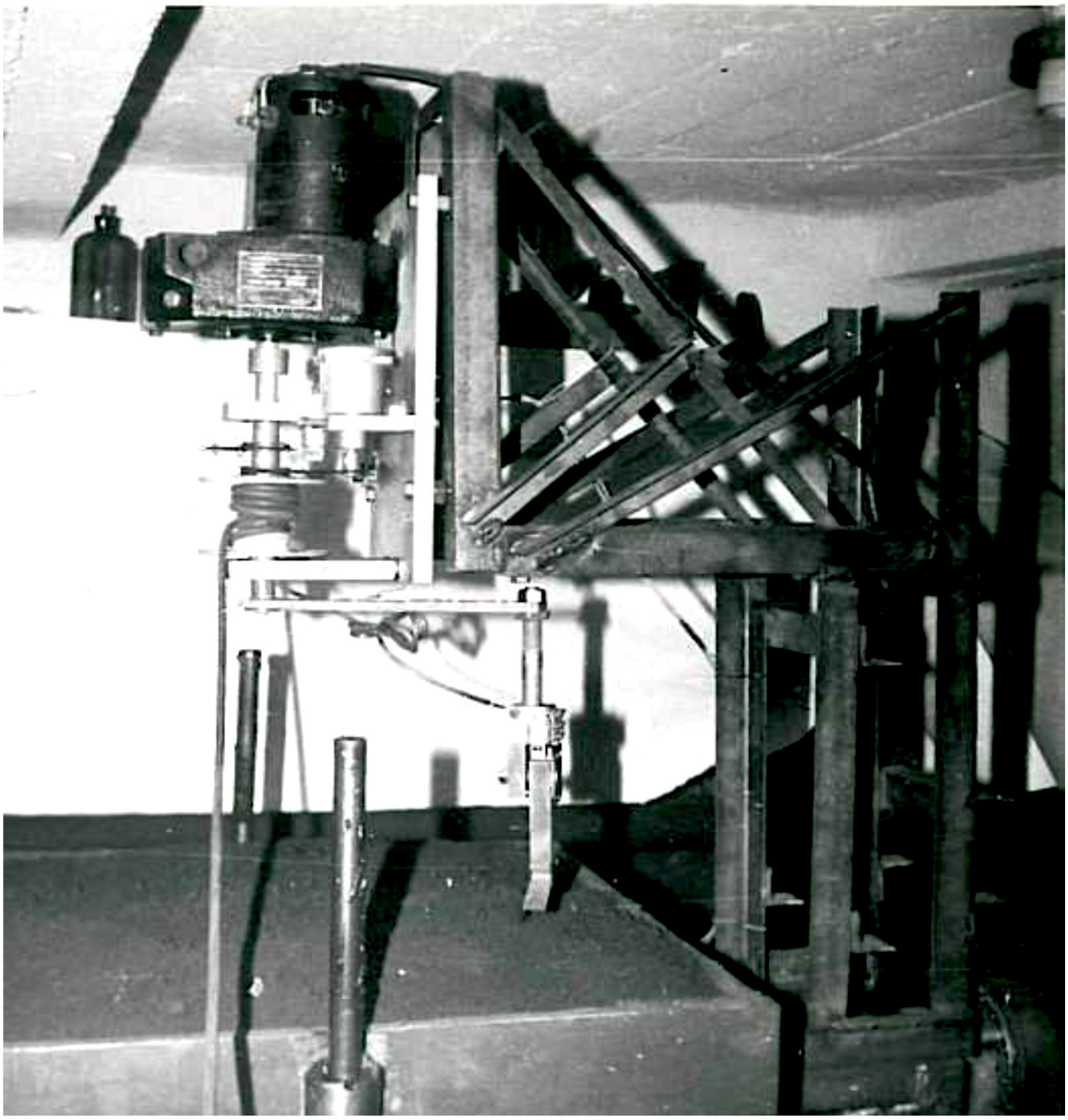
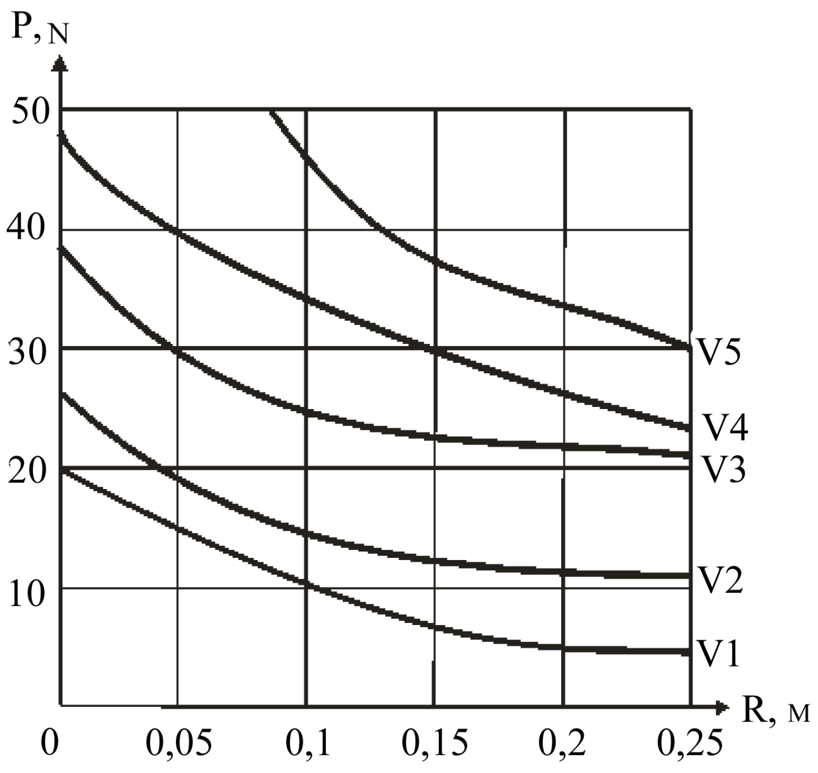
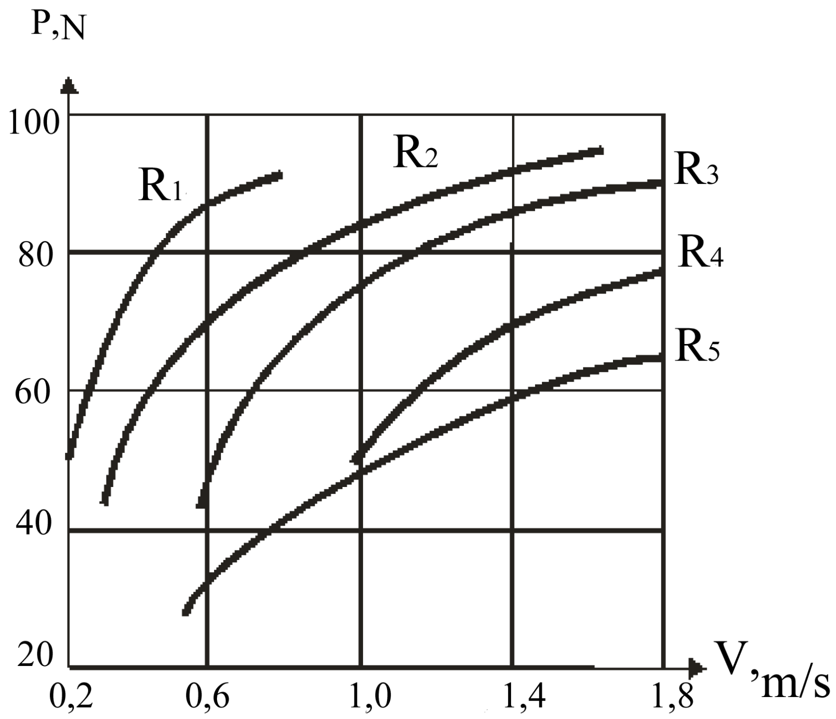


Figure 5. *The stand for a full-size test of milling working bodies*



a) V_1 = 0,05m/s; V_2 = 0,1 m/s; V_3 = 1 м/s; V_4 = 1,5 м/s; V_5 = 2,5 м/s.



b) R_1 = 0,05m; R_2 = 0,1 m; R_3 = 0,15 m; R_4 = 0,25 m; R_5 = 0,475 m/s.

Figure 6. *Dependence of the cutting force by a single cutting tool on the radius of milling (a) and speed of cutting.*

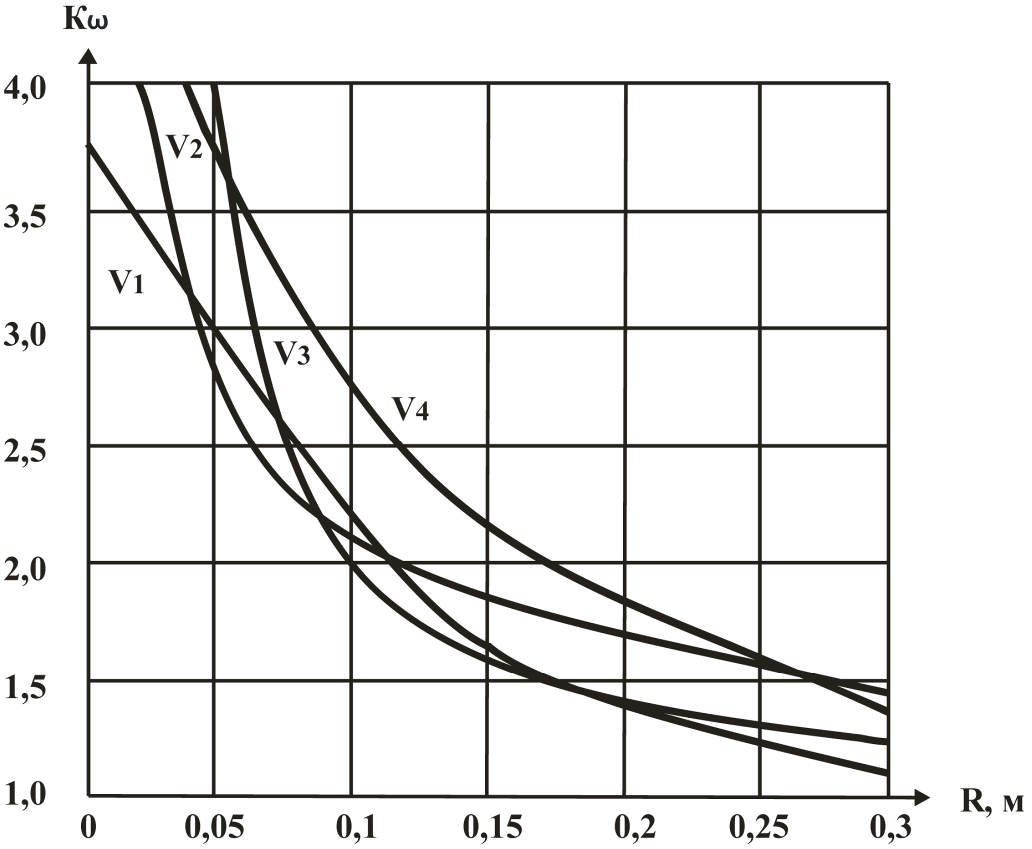


Figure 7. *Dependence of the coefficient K_ω on milling radius*

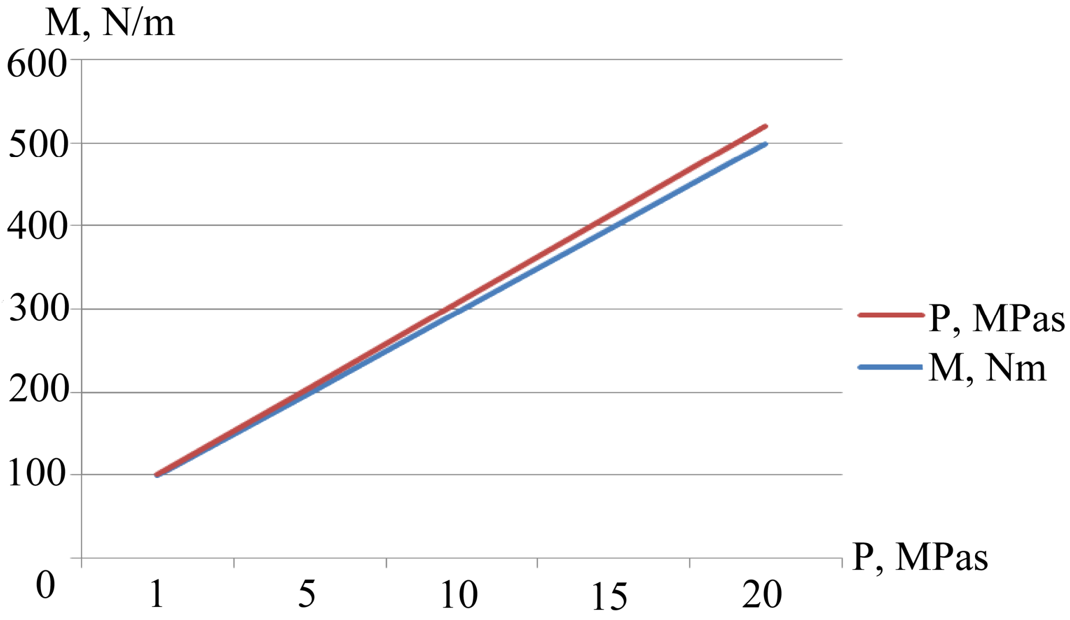


Figure 8. *Dependence of torque on pressure moment in the face*

Table 1. *The values of specific forces to giving and rotation of a mill*

The category of the ground m_{free}, parameter, N/m²	***Specific force A, kN/m***	***Specific force B, kN/m***
1 category, $5 \cdot 10^4$	81,3	83,6
2 category, $10 \cdot 10^4$	136,1	121,0
3 category, $25 \cdot 10^4$	278,0	248,2
4 category, $50 \cdot 10^4$	525,1	420,1
5 category, $100 \cdot 10^4$	1088,8	912,0
6 category, $150 \cdot 10^4$	1612,8	1315,1