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Establishing Forces of Soil Resistance to Cutting with Milling Working Bodies

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Abstract. *The features of the development of soils by a milling working body do not allow us to directly use the conclusions of various theories of cutting soils. The goal is to establish theoretical coefficients that take into account changing the cutting force during milling the soil. The article presents the first obtained dependences on changing the cutting force of soils during their milling at the depth of the bottom hole, hydrostatic and hydrodynamic pressures of the solution on the cut chips and the curvature of the tool path. The cutting force is affected by the hydrostatic pressures of the clay solution and the shear resistance. The coefficients of the working conditions are obtained. The coefficients describe the qualitative picture of soil cutting. They give the ratio of forces during rectilinear destruction of the soil to the forces arising during its milling.*

Keywords: *cutting forces, clay solution, milling, chip element, slurry wall.*

Introduction

Soil milling is used in the construction of underground structures using the «wall in the soil» method [1, 2, 3]. The destruction of the soil occurs in the environment of a clay solution that protects the walls of the trenches from collapse. The diameters of the cutters fluctuate significantly. Figure 1 shows the milling machine.

The general way of defining cutting forces is considering the equilibrium of the chip element to be cut off. In the period of time preceding the soil spalling in the chip element at the speed of sound, a shock wave of elastic stresses propagates, which ultimately leads to the formation of the spalling surface at the angle ψ to the tangent to the trajectory of the cutter. The front of the shock wave of deformations is directed along the normal to the frontal edge of the cutting tool. Elastic deformation stress only causes volumetric deformation of the soil. At the same time (in cohesive soils) a compacted core is formed in front of the cutter of the working body. Its formation occurs due to the compaction of the soil that has experienced elastic-plastic deformation that has turned into crushing deformation. A front of plastic deformations that do not cause changes in the shape of the soil mass propagates in front of the compacted core. Thus, within this period of time, the cutting force is a variable value and is characterized by the ratio of the rates of elastic and plastic deformations, as well as the masses of the soil experiencing one or another deformation.

For practical calculations of the cutting force, it is necessary to determine the maximum value of the cutting force that occurs at the moment that differs from the moment of spalling by an infinitely small amount of time.

Description of materials and methods of analysis. The element of the sheared shavings abc (Figure 2) is acted upon by the force of normal pressure N_p from the side of the cutter, the weight of the chips P, hydrostatic pressure $P_{g.c.}$, centrifugal force $P_{c.b.}$ arising as a result of movement around the axis along the radius R, reaction from the side of the soil at the spalling site R^{τ} and the normal to it force R^{σ}, the resistance force at the wear site $P_{iz.}$, as well as the additional force P_{dop}, the existence of which is due to the kinematic milling of the soil. The cutter has the cutting angle δ, the clearance angle ν, the width b, the wear area of the width a. The back edge of the cutter is acted upon by the force of hydrostatic pressure. The spalling area is inclined to the tangent to the cutting path at the angle ψ.

Let us express each of the forces acting on the spalling chip element depending on the geometric parameters and soil characteristics. At the first stage of the analysis, we will not take into account the forces

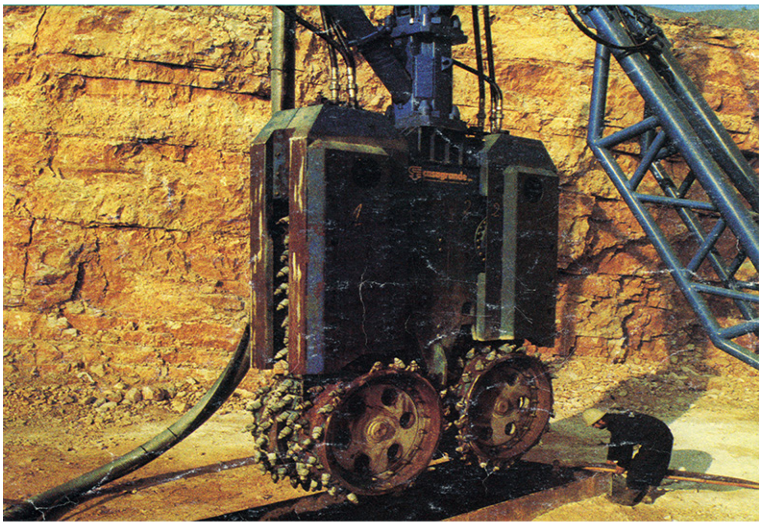

Figure 1 – Trenching plant of the Soletansh Company

$P_{dop.}$ and $P_{iz.}$ considering cutting with a sharp knife.

The chip element is characterized by the following geometrical parameters (Figure 2).

$$\delta.c. = h(\mathrm{ctg}\delta + \mathrm{ctg}\psi); \tag{1}$$

$$F_{g.c.} = bh(\mathrm{ctg}\delta + \mathrm{ctg}\psi); \tag{2}$$

$$V_c = \frac{bh^2}{2}(\mathrm{ctg}\delta + \mathrm{ctg}\psi), \tag{3}$$

where $\delta.c.$ is the length of the spalling element;

$F_{g.c.}$ is the surface area of the chip that is in the contact with the clay solution;

V_c is the chip volume.

Taking into account expression (3), the weight of the chip being cut off

$$P_c = \frac{bh^2\rho_2 g}{2}(\mathrm{ctg}\delta + \mathrm{ctg}\psi). \tag{4}$$

The centrifugal force

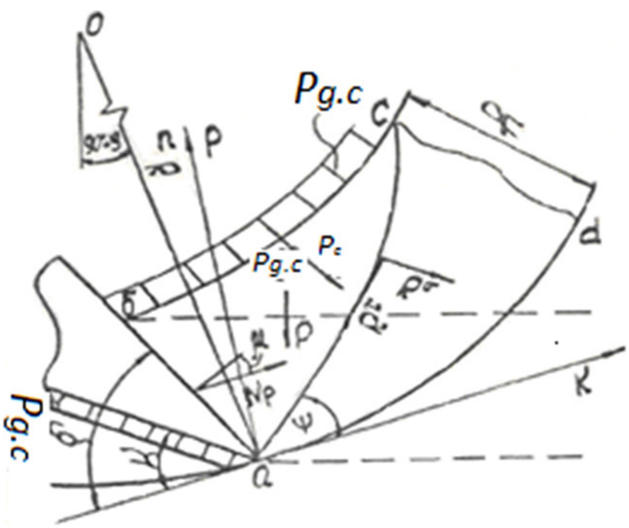

Figure 2 – The diagram of forces acting on the chip element when milling

$$P_{c.b.} = \frac{V_c\rho_2 V_0^2}{2R} = \frac{bh^2\rho_2 V_0^2}{2R}(\mathrm{ctg}\delta + \mathrm{ctg}\psi). \tag{5}$$

The resultant force of hydrostatic pressure on the element of the chip being cut off

$$P_{g.c.} = bhq(\mathrm{ctg}\delta + \mathrm{ctg}\psi). \tag{6}$$

The value of the distributed pressure of the solution on the ground g depends on the values of the head, the density of the solution and the pressure transfer coefficient η. According to A.A. Shatalov [4], η reaches the highest values in soils with the lowest permeability (equal to unity for dense clays) and the smallest values in sands and gravelly soils.

In our opinion, the physical picture of the effect of the permeability degree of soils on the process of transferring pressure deep into the massif and on the cutter is that as the depth of filtration of the clay solution into the soil l_φ increases, the pressure difference on the cutter along the frontal and rear edges decreases. The liquid penetration for a part of the chip thickness limits the zone of uneven reduction of the cutter. With complete solution filtration, the cutter is compressed from all the sides by hydrostatic pressure and does not experience additional loading. In this case, changing the cutting force occurs due to changing the rheological characteristics of the soil.

Based on these considerations, it is natural to assume that there is a relationship between the filtration depth l_φ, the thickness of the chips h and the pressure transfer coefficient

$$\eta = 1 - \frac{l_\varphi}{h}. \tag{7}$$

In accordance with relationship (7), for dense bonded soils l_φ=0, the coefficient μ=1. For loose soils, the depth of mud filtration can approach the values of the chip thickness, and the pressure transfer coefficient can approach zero.

Proposed formula (7) does not take into account the time the bottomhole is in contact with the clay solution. Therefore, for milling and drilling machines that differ in speed when cutting chips, it is more correct to determine the pressure transfer coefficient according to the dependence:

$$\eta = 1 - \frac{V_\varphi}{V}, \tag{8}$$

where V_φ is the filtration rate.

In work [5], the filtration rate of the clay solution into the soil was determined depending on piezometric pressure, the coefficient of soil porosity, the viscosity of the clay solution and its limiting shear stress. Naturally, the filtration rate of the clay solution into the soil is lower than that of water. Taking the worst version of the calculation and assuming that permeability of the soil to the solution is equal in the limit of permeability during the movement of water, we determine the maximum possible filtration rate that is described by the Darcy law:

$$V_\varphi = K_\varphi J, \tag{9}$$

where K_φ is the filtration coefficient;

J is piezometriic pressure.

Focusing on the values of the filtration coefficient established by soil scientists [7] ($1 \cdot 10^{-7}$ m/s for clays and $1 \cdot 10^{-3}$ m/s for gravel and coarse-grained sandy soils), we find that for any practical possible piezometric pressure head the filtration rate of the clay solution is comparable to the feed rate. $V = 0.5 \ldots 1 \cdot 10^{-2}$ m/s only in coarse sands and gravel soils. In these soil conditions, the construction of foundations by the «slurry wall» method is unacceptable even when protecting the walls of the trench from collapse with a clay mortar. It can be argued that during the operation of milling and boring machines, the pressure transfer coefficient is practically equal to unity, and physical and mechanical characteristics of the soil do not have time to change. Taking into account (9), we obtain:

$$P_{g.c.} = bhzg\left(1 - \frac{V_\varphi}{V}\right)(\mathrm{ctg}\delta + \mathrm{ctg}\psi). \tag{10}$$

The kinematic feature of milling is variability of the thickness of the cut chips during the cutter movement (Figure 3).

In this case, the cutter makes a working movement only in the third and fourth quarters of the circle. The average values of the cut chips thickness and consequently the resistance forces that depend on it, will be observed at the angle of rotation of the cutter. The values of this angle determined by the author from the integral dependences of the center of gravity of a flat figure [8] are for the third quarter:

$$\varphi_{mid} = 57^\circ \approx 60^\circ,$$

for the fourth quarter:

$$\varphi_{mid} \approx \frac{\pi}{2} + 60^\circ.$$

When considering the element of the cut off chips at points 1 and 2, changing the direction of forces is possible. The centrifugal force and the force

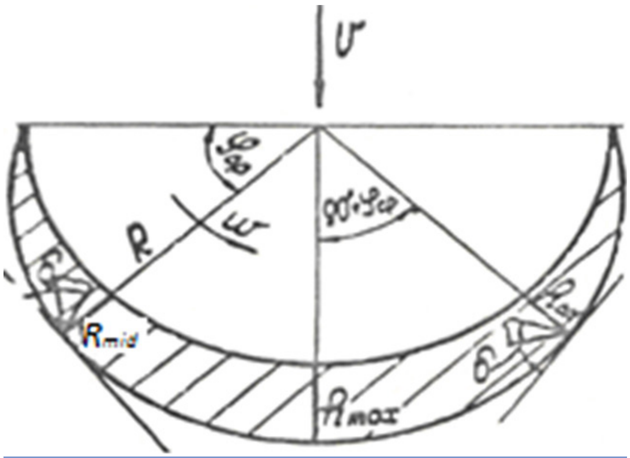

Figure 3 – The section of the chip to be cut when soil milling

of hydrostatic pressure directed radially remain unchanged. The gravity force of the chip element when projected on the τ and δ axes has different signs, since in the third quarter this force increases the action of the normal pressure force, and in the fourth quarter it decreases it.

The kinematic feature of milling is such that at small values of the chip thickness, the soil is crushed by the wear area and even by a sharp cutter. This is due to the fact that small values of the chip thickness do not provide volumetric destruction of the soil needed for the cutting process. At the same time, since the resistance to friction and crushing of the soil is greater than cutting resistance, the overall loading of the cutter increases.

In addition, during the rotational movement of the cutters, energy is lost due to elastic deformation of the undisturbed soil around the face. The magnitude of these losses is proportional to the elastic limit and the total mass of the soil undergoing elastic deformations, and is inversely proportional to the square of the elastic modulus.

It is impossible to calculate the additional force $P_{dop.}$, since it is not clear from what value of the chip thickness the friction process is replaced by the cutting process and what is the mass of the soil outside the face experiencing elastic deformations.

Let us project the forces acting on the element of the cut off chips on the axes τ and σ. In this case, we lay the normal reaction from the side of the cutter N_p from the normal to the frontal face by the angle of internal friction, thereby taking into account the friction force of the chips on the cutter.

We obtain:

$$\begin{cases} N_p \pm P_c^\tau - P_{g.c.}^\tau - P_c^\tau - R^\tau = 0; \\ N_{pp}^\sigma \pm P_c^\sigma - P_{g.c.}^\sigma - P_c^\sigma - R^\sigma = 0, \end{cases} \tag{11}$$

where

$$N_p^\tau = N_p \sin(\delta + \mu + \psi);\ N_p^\sigma = N_p \cos(\delta + \mu + \psi); \tag{12}$$

$$P_c^\tau = P_c \sin\varphi \sin\psi;\ P_c^\sigma = P_c \sin\varphi \sin\psi; \tag{13}$$

$$P^{\tau}_{g.c.} = P_{g.c.}\sin\psi;\ P^{\sigma}_{g.c.} = P_{g.c.}\sin\psi; \qquad (14)$$

$$P^{\tau}_{c.b.} = P_{c.b.}\sin\psi;\ P^{\sigma}_{c.b.} = P_{c.b.}\sin\psi. \qquad (15)$$

A number of authors [9, 10] determined for soils the values of shear resistivity K_4. The values of soil adhesion C and the tangent of the angle of friction $\mathrm{tg}\rho$ in soil mechanics [11, 12, 13] are determined experimentally. These parameters are determined at the shear of the normal stress therefore, different densities. Since the density of soils under the effect of compression pressure generally increases with depth, the rheological parameters of the soil determined in this way are averaged. There are empirical relationships that interconnect the soil cohesion and the angle of internal friction with the density and therefore, the depth of the soil. These dependences, however, have a small area of application and cannot be used in general theoretical analysis.

In the Building codes and regulations, when calculating the permissible settlement of foundations, another method was adopted for taking into account the depth of the soil by the value of its bearing capacity. In this case, the values of adhesion and the angle of internal friction remain unchanged, and normal stresses increase by the value of compression pressure σ_δ:

$$\sigma_\delta = \frac{1+2\xi}{3} z\gamma_{sr} = \frac{(1+2\xi)\gamma_з}{3(1+\varepsilon)} z = z\rho_{gr} g\xi', \qquad (16)$$

where ξ is the soil transverse deformation coefficient;

$\gamma_з$ is specific weight of the soil grains;

ε is the porosity coefficient;

ξ' is a conditional coefficient of the soil transverse deformation accepted for convenience of recording.

The K_4 values were determined for the upper soil layers. By introducing compression pressure for the upper soil layers into the shear stress, we obtain:

$$\tau = c + (\sigma + \sigma_б)\,\mathrm{tg}\rho = K_4 + \sigma_б\,\mathrm{tg}\delta. \qquad (17)$$

Dependence (17) describes averaged changing the shear stress of the soil as the face deepens.

At the time of the breakdown of the soil, it is true that

$$\frac{R^\tau}{F_{ск}} + \frac{R^\sigma\,\mathrm{tg}\rho}{F_{ск}} = \tau, \qquad (18)$$

where $F_{ск}$ is the spalling area,

$$F_{ск} = \frac{bh}{\sin\psi}. \qquad (19)$$

Substituting the expressions R^τ and R^σ determined from system (11) into equation (18), expanding the expressions for the forces emerging into R^τ and R^σ and equating the obtained resistance forces to the value of N_p, we obtain:

$$N_p = \frac{K_4 bh}{\alpha_1\sin\psi} + \frac{\sigma_v bh}{\alpha_1\sin\psi} \pm \frac{bh^2\rho_2\alpha_2\sin\varphi}{2\alpha_1} + \frac{bh\rho_2 zg\alpha_2}{\alpha_1}\left(1-\frac{V_\varphi}{V}\right) + \frac{bh^2\rho_2 V_0^2\alpha_2}{2R\alpha_1} - P_{dop.}, \qquad (20)$$

where

$$\alpha_1 = \sin(\delta+\mu+\psi) + \mathrm{tg}\rho\cos(\delta+\mu+\psi),$$
$$\alpha_2 = \mathrm{ctg}(\delta+\mathrm{ctg}\psi)(\sin\psi + \cos\psi\,\mathrm{tg}\rho).$$

The force arising on the frontal surface of the cutter cannot fully characterize cutting resistance, since it does not take into account hydrostatic pressure on the back face of the cutter. Having projected the N_p force and the resultant of hydrostatic pressure on the cutter on the k and n axes, we obtain:

$$\begin{aligned} P_k &= N_p\sin(\delta+\mu) - P_{g.c.}bh; \\ P_n &= N_p\cos(\delta+\mu) \mp P_{g.c.}bh, \end{aligned} \qquad (21)$$

where $P_{g.c.}$ is distributed solution pressure on the back face of the cutter.

The plus or minus sign is placed in front of the second term of the second equation of system (21) depending on whether the cutter is pulled into the ground or pushed out.

Expanding the expression for the force N in system (21), we find:

$$\begin{aligned} P_k &= \frac{K_4 bh}{\alpha_3\sin\psi} + \frac{P_g\xi_1 zgbh}{\alpha_3\sin\psi} \pm \frac{bh\rho_g g\alpha_2\sin\varphi}{2\alpha_3} + \\ &+ bh\rho_c zg\left[\frac{\alpha_2}{\alpha_3}\left(1-\frac{V_\varphi}{V}\right) - 1\right] + \frac{bh^2\rho_2 V_0^2\alpha_2}{2R\alpha_3}; \\ P_n &= \frac{K_4 bh}{\alpha_4\sin\psi} + \frac{P_g\xi_1 zgbh}{\alpha_4\sin\psi} \pm \frac{bh\rho_g\alpha_2\sin\varphi}{2\alpha_4} + \\ &+ bh\rho_c zg\left[\frac{\alpha_2}{\alpha_4}\left(1-\frac{V_\varphi}{V}\right) \mp 1\right] + \frac{bh^2\rho_2 V_0^2\alpha_2}{2R\alpha_4}, \end{aligned} \qquad (22)$$

where $\alpha_3 = \dfrac{\alpha_1}{\sin(\delta+\mu)}$, $\alpha_4 = \dfrac{\alpha_1}{\cos(\delta+\mu)}$.

The obtained expressions for P_k determine the cutting force during milling.

It follows from the right-hand side of the equations of system (22) that the cutting force during milling depends on the soil resistance to shear, the depth of the face, the density of the soil, the density of the solution, the cutting speed, the feed rate of the working body, the rate of filtration of the solution into the soil, the geometry of the cutter, the radius of the tool rotation.

Let us analyze the effect of various components of the cutting force on its total value. For this purpose, we represent the tangential force in the form:

$$P_k = P_1 + P_2 + P_3 + P_4 + P_5,$$

where P_1 is the component of resistance force depending on the soil resistance to shear;

P_2 is the component of the cutting force taking into account compression pressure of the cutter;

P_3 is the part of the cutting force caused by the cut off chip weight;

P_4 is the cutting force occurring due to the action of hydrostatic pressure;

P_5 is the component of the cutting force occurring as a result of the action of the centrifugal inertia force.

Equation (22) gives a qualitative picture of the cutting force with a sharp knife interconnecting components of resistance to milling that are different in their physical essence. Let us express in relative units the effect of the components of the cutting force on the cutting forces of the soil during the rectilinear movement of the cutter on the daylight surface without the action of hydrostatic pressure on the bottomhole.

The ratio of the forces arising during soil milling to the forces of the straight cut will be called the rotational cutting coefficient K_ω, the ratio of the forces of hydrostatic pressure to compression pressure the coefficients of hydrostatic pressure K_p and the driving depth K_z:

$$K_\omega = \frac{P_1 + P_3 + P_5}{P_1 + P_3} = 1 + \frac{P_5}{P_1 + P_3}; \qquad (23)$$

$$K_p = \frac{P_1 + P_3 + P_4}{P_1 + P_3} = 1 + \frac{P_4}{P_1 + P_3}; \qquad (24)$$

$$K_z = \frac{P_1 + P_2 + P_3}{P_1 + P_3} = 1 + \frac{P_2}{P_1 + P_3}, \qquad (25)$$

where $P_1 + P_3$ is the cutting force with the cutter rectilinear movement without hydrostatic pressure on the bottomhole.

The total coefficient K_φ taking into account resistance to milling when operating in the solution will be

$$K_\varphi = \frac{P_1 + P_2 + P_3 + P_4 + P_5}{P_1 + P_3} = K_p + K_z + K_\omega - 2. \qquad (26)$$

The number 2 in the equation is needed since the cutting force is taken into account thrice [13].

The most significant effect on the cutting force is rendered by hydrostatic pressure of the mud and the shear resistance. By adding to the cutting force P_k resistance to cutting on the wear area, the total cutting force can be determined. In further calculations, the P_3 and P_5 forces will not be taken into account.

Conclusions

1. The components that depend on the shear stress of the soil and hydrostatic pressure have the greatest weight in the structure of the cutting force.
2. The values of mass forces, the chip weight and the centrifugal force do not affect significantly the cutting force.
3. The rate of the clay solution filtration into the soil affects the cutting force only in sandy and gravel soils.

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Фрезерлік жұмыс органдарымен кесуге топырақтың кедергі күштерін орнату

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Аңдатпа. *Фрезерлік жұмыс органының топырақты дамыту ерекшеліктері бізге топырақты кесудің әртүрлі теорияларының тұжырымдарын тікелей қолдануға мүмкіндік бермейді. Зерттеудің мақсаты -топырақты фрезерлеу кезінде кесу күшінің өзгеруін ескеретін теориялық коэффициенттерді орнату болып табылады. Мақалада ұңғыманың түбінде фрезерлеу кезінде топырақтың кесу күшінің өзгеруіне, кесілген жоңқаның ерітіндінің гидростатикалық және гидродинамикалық қысымына және құралдың траекториясының қисықтығына байланысты алғашқы алынған тәуелділіктер келтірілген. Кесу күшіне саз ерітіндісінің гидростатикалық қысымы және ығысу кедергісі әсер етеді. Жұмыс жағдайларының коэффициенттері алынды. Коэффициенттер топырақтың сапалы кескінін сипаттайды. Олар топырақтың тік сызықты бұзылуы кезінде күштердің фрезерлеу кезінде пайда болатын күштерге қатынасын береді.*

Кілт сөздер: *кесу күштері, сазды ерітінді, фрезерлеу, жоңқа элементі, топырақтағы қабырға.*

Установление сил сопротивления грунта резанию фрезерными рабочими органами

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Аннотация. *Особенности разработки грунтов фрезерным рабочим органом не позволяют напрямую использовать выводы различных теорий резания грунтов. Целью является установление теоретических коэффициентов, учитывающих изменение силы резания при фрезеровании в сравнении с прямолинейным. В статье приведены впервые полученные зависимости по изменению силы резания грунтов при их фрезеровании от глубины проходки забоя, гидростатического и гидродинамических давлений раствора на срезаемую стружку и кривизны траектории движения резца. На силу резания действуют гидростатическое давление глинистого раствора и сопротивление сдвигу. Получены коэффициенты условий работы. Коэффициенты описывают качественную картину среза грунта. Они дают соотношение сил при прямолинейном разрушении грунта к силам, возникающим при ее фрезеровании.*

Ключевые слова: *силы резания, глинистый раствор, фрезерование, элемент стружки, стена в грунте.*

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