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ANALYTICAL DETERMINATION OF ENERGY INTENSITY OF CRITICAL DEEP CUTTING OF SOILS BY MULTI-SCRAPER TRENCH EXCAVATORS

The object of research is the processes of interaction of the cutters of the working body of the chain trench excavator on the basis of the semi-blocked critical depth mode of soil cutting. One of the most problematic places is that the known analytical and experimental models of interaction of multi-scraper chain trench excavators with soil do not determine the parameters and modes of their operation based on critical depth cutting of soils. Therefore, the design of work equipment for given conditions on the basis of such dependencies does not provide the minimum energy consumption and maximum productivity of the work process.

The research used the method of analytical calculation of parameters of installation of soil-developing elements and determination of energy performance of multi-scraper chain working body of trench excavator on the basis of semi-blocked critical-depth soil cutting regime.

The proposed calculation method allows to determine the parameters of installation of the working body and placement of soil development elements and to quantify the energy performance of multi-scraper chain working body of the trench excavator based on semi-blocked critical depth of soil cutting mode.

The obtained method of calculation, in contrast to existing empirical estimates, allows developing options for improving the parameters of multi-scraper chain working body. As a substantiation of this conclusion the conceptual variant of technical realization of the working equipment is offered, namely, allows to prove expediency of the choice of the semi-blocked scheme of arrangement of cutters of critical deep cutting of soil of a working body of a trench multi-scraper excavator.

The conducted energy analysis showed that it is more expedient to use a multi-scraper chain working body of a trench excavator on the basis of a semi-blocked critical-depth regime of soil cutting. For example, for soil semi-solid clay with blocked cutting, cutting angle α_c=20–30°, cutter width b=0.02 m the energy intensity of the working process varies within E=191–233 kJ/m^3; for semi-blocked cutting under the same conditions – E=187–191 kJ/m^3, which is 2–18 % less.

Keywords: *excavator, chain-scraper working body, critical deep cutting of soils, cutting force, energy consumption.*

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1. Introduction

Technological development of society involves an increase in the volume of underground communications. Trench excavators with chain-scraper working bodies are widely used to solve this problem [1–3].

From the point of view of energy efficiency, the most important component of the process of digging the soil with a chain-scraper working body is the process of cutting the soil with knives. The minimum energy consumption of this process is ensured during the operation of knives in the conditions of critical depth of soil cutting mode [4–6]. Existing studies do not include a comparative analysis of the energy efficiency of multi-scraper chain working bodies of trench excavators based on blocked and semi-blocked critical-depth regime of soil cutting due to the lack of calculation methods.

Therefore, it is important to create methods for calculating the parameters of the multi-scraper chain working body of the trench excavator on the basis of blocked and semi-blocked critical depth mode of soil cutting.

Thus, *the object of research is* the processes of interaction of the cutters of the working body of the chain trench excavator on the basis of the semi-blocked critical depth mode of soil cutting.

The aim of research is to create a method for calculating the energy performance of the working equipment of a multi-scraper chain working body of a trench excavator on the basis of a semi-blocked critical depth regime of soil cutting.

2. Research methodology

The following initial data are accepted for calculation: technical productivity P_{tech}, m^3/h; maximum trench depth H, m; trench width B, m; physical and mechanical characteristics of soils (coefficient of adhesion, specific gravity, angles of internal and external friction).

Provided that the length of one drive chain l_c is equal to three steps between groups of scrapers T, determine the height of the working body above the day surface H_0 (Fig. 1):

$$l_c = \frac{2(H+H_0)}{\sin\alpha} = 3T = \frac{3H}{\sin\beta} \text{ m,} \quad (1)$$

where α – the angle of installation of the working body to the horizon, deg; β – the angle between the vectors of soil cutting speeds and the supply of the working body, deg.

If accepted $\alpha \approx \beta$, then:

$$H_0 \approx \frac{H}{2} \text{ m.} \quad (2)$$

Under the accepted condition, the number of groups of cutters will be $Z_{gr}=3$.

In the case of installation in a row of 2 cutters, the number of their beams is equal to:

$$Z_b = 1 + \frac{i_l - 1}{2} = \frac{i_l + 1}{2} \text{ it.,} \quad (3)$$

where i_l – the number of cutting lines.

The number of beams must be rounded up to an integer.

Step of installation of beams (Fig. 2):

$$t_b = \frac{T}{Z_b} = \frac{}{Z_b \sin\beta} \text{ m.} \quad (4)$$

The number of groups of knives that are simultaneously in the face is determined by:

$$Z_{gr}^f = \frac{l_f}{T} = \frac{H/\sin\beta}{H/\sin\beta} = 1 \text{ it.} \quad (5)$$

Height of scrapers h_s are determined from the condition that 2 beams are installed on the beam and the soil destroyed by them fills the inter-scraper volume between adjacent conveying scrapers, installed with step t_b (4):

$$h_s^{sbl} = \frac{2 \cdot h_{cr} \cdot Z_b \cdot Z_{gr}^f}{B}\left(b_{sbl} + h_{cr} \cdot k_c \cdot ctg\gamma\right) \cdot k_{lA}, \quad (6)$$

where h_{cr} – critical depth of cut, m; b_{sbl} – width of the cutter working in the conditions of semi-blocked cutting, m; k_c – the ratio of the depth of soil chipping to the critical depth of cut at the time of formation of the chip element (k_c=0.9...0.95); k_{lc} – soil loosening coefficient.

Number of cutters that simultaneously develop the soil:

– with blocked cutting:

$$n_{bl} = i_l; \quad (7)$$

– at semi-blocked cutting:

$$n_{bl} = 1, \text{ and } n_{sbl} = i_l - 1. \quad (8)$$

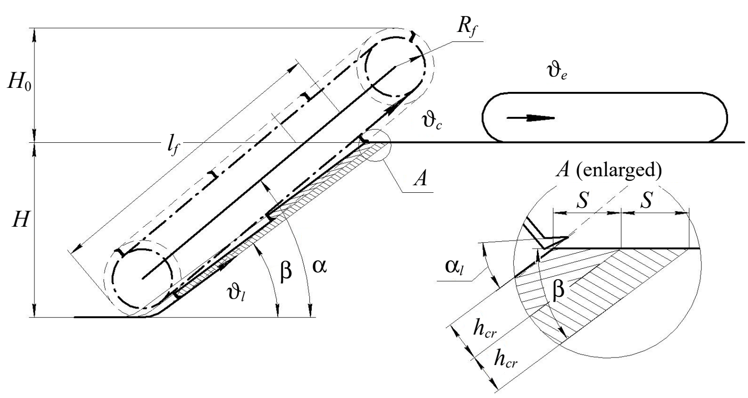

Fig. 1. Calculation scheme of interaction of the working body with the soil

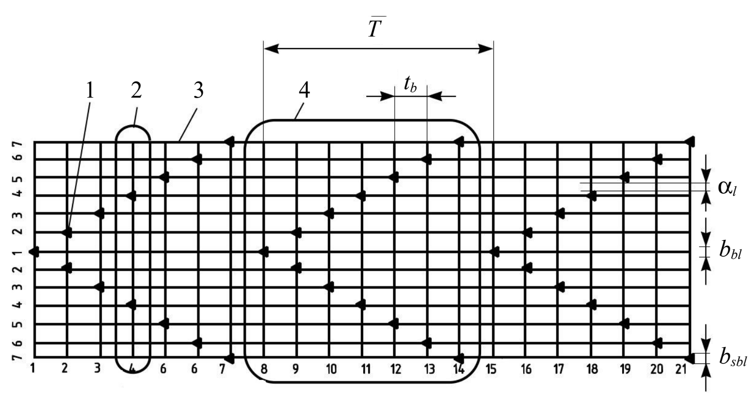

Fig. 2. Step scheme of arrangement of scrapers (knives):
1 – scraper; 2 – a number of scrapers; 3 – line of scrapers; 4 – group of scrapers; 1...21 – numbers of scrapers

The angle of displacement of the soil in the longitudinal plane (in the direction of movement of the soil-developing bodies) is determined by:

$$\psi = a_\psi + k_\psi \cdot \alpha_c \text{ rad}, \quad (9)$$

where α_c – the cutting angle of the knives at which the energy consumption is minimal (α_c=25–35°); α_ψ, k_ψ – the interpolation coefficients for a stable cutting regime, which depend on the soil type [8].

For medium cutters that perform blocked cutting, the length of the ploughshare is determined by:

$$l_P = \frac{l_m}{k_{bl}} = \frac{-B_* - \sqrt{B_*^2 - 4A_* \cdot C_*}}{2A_* \cdot k_c} \text{ m}, \quad (10)$$

where

$$\begin{cases} A_* = -\sin^2\alpha_c(\text{ctg}\alpha_c + \text{ctg}\psi)c, \\ B_* = 2\sin\alpha_c(\text{ctg}\alpha_c + \text{ctg}\psi)c \cdot h_{cr} - \dfrac{\sin(\alpha_c + \varphi + \varphi_0 + \psi)}{\cos\varphi \cdot \cos\varphi_0} b \cdot q_{av}, \\ C_* = \dfrac{c \cdot h_{cr}}{\sin\psi}\left(b + \arcsin\left(\dfrac{\text{tg}\psi}{\text{tg}\gamma}\right)h_{cr} \cdot \text{ctg}\psi\right); \end{cases}$$

φ_0 – the angle of internal friction of the soil, deg; q_{av} – the average value of pressure on the soil-developing body, determined accordingly [8], MPa.

For other cutting schemes (asymmetric blocked and semi-blocked cutting with extreme side cutters and semi-blocked cutting with middle cutters) the length of plowshares is defined in the literature [7].

Average blade pressure [8]:

$$q_{av} = (0.75...0.8) \cdot q_{cr} \text{ MPa}, \quad (11)$$

where q_{cr} – critical pressure on the soil according to its bearing capacity [8], MPa.

$$q_{cr} = \left(\gamma_{gr} \cdot h_{cr} + \frac{c}{\text{tg}\varphi_0}\right)\text{tg}^4\left(\frac{\pi}{4} + \frac{\varphi_0}{2}\right) \text{ MPa}, \quad (12)$$

where γ_{gr} – specific gravity of the soil, MN/m^3.

The strength of the blocked (semi-blocked) cutting with one cutter is determined by:

$$P_{1bl} = q_{av} \cdot l_P \cdot b_{bl} \cdot \sin\alpha_c(1 + f \cdot \text{ctg}\alpha_c) \text{ MN}, \quad (13)$$

where b_{bl} – width of cutters that perform blocked cutting.

Total cutting force with all knives:

– for blocked cutting:

$$P_\Sigma = (i_l^{bl} - 2) \cdot P_{1bl} + 2P'_{1bl} + P_{\Sigma f} \text{ MN}, \quad (14)$$

where P'_{1bl} – force of asymmetric blocked cutting by extreme side cutters:

$$P'_{1bl} = q_{av} l'_{bl} b'_{bl} \sin\alpha_c (1 + f \cdot \text{ctg}\alpha_c) \text{ MN}, \quad (15)$$

$P_{\Sigma f}$ – the total force of free cutting of the soil, which remained intact in the front plane between the knives; l'_{bl}, b'_{bl} – respectively, the length and width of the ploughshare of the extreme side cutters [7]:

$$P_{\Sigma f} = \left[-(\sin\psi_f + \text{tg}\varphi_0 \cdot \cos\psi_f)\frac{\cos(\alpha_c + \varphi + \psi_f)}{\cos\varphi \cdot \sin\alpha_c} \times \right.$$
$$\left. \times q_0 \cdot h_{cr}^2 \cdot \text{ctg}\gamma + ch_{cr}^2 \text{ctg}\gamma \cdot \text{ctg}\psi_f\right] \cdot (i_l - 1) \text{ MN}, \quad (16)$$

where

$$\psi_f = 90° - \frac{\alpha_c + \varphi + \varphi_0}{2} \text{ deg.}, \quad (17)$$

q_0 – the minimum normal soil pressure on the scraper in contact with intact trapezoidal protrusions left between the knives:

$$q_0 = c \cdot (A_1 - 1)\text{ctg}\varphi_0 \text{ MPa}, \quad (18)$$

A_1 – coefficient that depends on the cutting angle and the angle of internal friction of the soil [9];

– for semi-locked cutting:

$$P_{\Sigma c} = P_{1bl} + (i_l^{sbl} - 2)P_{1sbl} + 2P'_{1sbl} \text{ MN}, \quad (19)$$

where P'_{1sbl} – force of asymmetric semi-locked cutting with extreme side cutters:

$$P'_{1sbl} = q_{av} l'_{sbl} b'_{sbl} \sin\alpha_c (1 + f \cdot \text{ctg}\alpha_c) \text{ MN}, \quad (20)$$

where l'_{sbl}, b'_{sbl} – respectively, the length and width of the plowshares of the extreme side cutters that perform asymmetric semi-locked cutting [7].

Resistance force of transportation of cut soil on the surface of the face [10]:

$$P_{tr} = \frac{B \cdot h_{cr} \cdot H \cdot \gamma_{gr}}{k_l \cdot \sin\beta}(1 + \text{tg}\varphi_0 \cdot \text{ctg}\alpha)\sin\alpha \text{ MN}, \quad (21)$$

where k_l – coefficient of soil loosening (k_l=1.08...1.32 for soils of I–IV category [10, 11]).

Chain tension force required to lift the soil from the face:

$$P_l = B \cdot h_s \cdot \gamma_{gr}\left(\frac{H}{2} + H_0\right)\frac{k_f}{k_l \cdot \sin\alpha} \text{ MN}, \quad (22)$$

where h_s – the height of the scraper ($h_s \approx h_{cr}$); k_f – coefficient of filling of the inter-scraper space (for soils of I–IV categories, respectively, 0.9...1.2 and 0.7...0.9 [10, 11]).

Total effort in the chain:

$$P_\Sigma = P_{\Sigma c} + P_{tr} + P_l. \quad (23)$$

Energy consumption of destruction of one running meter of a trench:

$$E = \frac{P_\Sigma \cdot 1.0}{Bh_{cr} \cdot 1.0} \text{ MJ/m}^3. \quad (24)$$

Torque for drive shaft:

$$M_T = 10^6 \cdot P_\Sigma \cdot R_s \text{ Nm}, \quad (25)$$

where R_s – the radius of the drive star:

$$R_s = \frac{t_{ch}}{2\sin\dfrac{180°}{n_z}} \text{ m}, \quad (26)$$

where t_{ch} – the pitch of the chain (t_{ch}=0.1...0.2 m); n_z – the number of teeth of the drive sprocket (n_z=9...13°).

Required engine power to drive the chain-scraper working body:

$$N_{dr} = \frac{10\cdot {}_{\Sigma}\cdot \upsilon_c}{\eta_{dr}\cdot \eta_c}\ \text{kW}, \qquad (27)$$

where η_{dr}, η_c – drive and circuit efficiency.

The balance of engine power and the choice of the base machine are carried out in accordance with the literature [8, 10, 11].

3. Research results and discussion

Studies have been conducted for semi-solid clay soil (which has the most difficult conditions for digging soil with trench excavators), cutting angles α_c=20...50°, cutter widths b=0.01...0.02 m, the width of the trench B=0.2...1 m.

As a result of numerical calculations, the following graphical dependences were obtained:

– dependences of cutting forces on the width of the trench for blocked and semi-blocked schemes of arrangement of cutters are given, respectively, in Fig. 3, 4;

– dependences of the maximum effort in the chain are shown in Fig. 5, 6;

– dependences of energy consumption on the cutting angle and trench width for the blocked scheme of arrangement of cutters are given in Fig. 7, and for the semi-blocked – in Fig. 8.

From the analysis of the conducted researches it follows:

1) the height of soil-scraping scrapers increases in direct proportion to the width of the cutters (6);

2) the total force of critical depth cutting of the soil for blocked and semi-blocked scheme of incisors increases with increasing trench width and decreases with increasing cutting angle (Fig. 3, 4) because with increasing cutting angle decreases the critical cutting depth;

3) energy consumption of the working process takes the minimum values at the cutting angle α_c=20° and with increasing trench width from B=0.25 m to B=1 m:

– for blocked cutting – slightly increases;

– for semi-blocked – slightly reduced;

4) energy consumption of the soil digging process for semi-solid clay, cutting angles α_c=20–30°, width of cutters b=0.02 m varies within:

– for blocked cutting E=191–233 kJ/m^3 (Fig. 7);

– for semi-blocked cutting E=187–191 kJ/m^3 (Fig. 8).

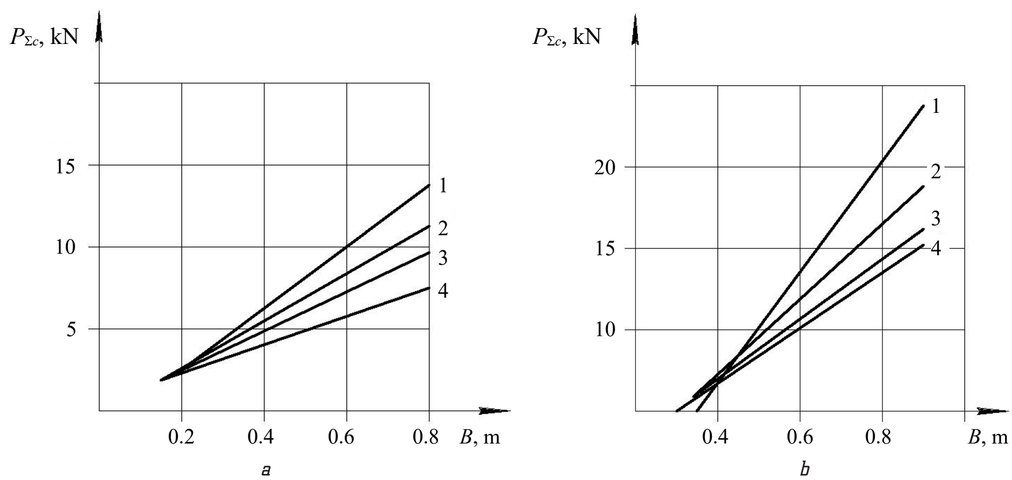

Fig. 3. Dependence of the total force of critical depth cutting of the soil on the width of the trench for the blocked scheme of arrangement of cutters (soil – semi-solid clay): *a* – b_{bl}=0.02 m (1 – α_c=20°, b'_{sbl}=0.039 m; 2 – α_c=30°, b'_{sbl}=0.033 m; 3 – α_c=40°, b'_{sbl}=0.031 m; 4 – α_c=50°, b'_{sbl}=0.031 m); *b* – b_{bl}=0.03 m; (1 – α_c=20°, b'_{sbl}=0.058 m; 2 – α_c=30°, b'_{sbl}=0.049 m; 3 – α_c=40°, b'_{sbl}=0.046 m; 4 – α_c=50°, b'_{sbl}=0.046 m)

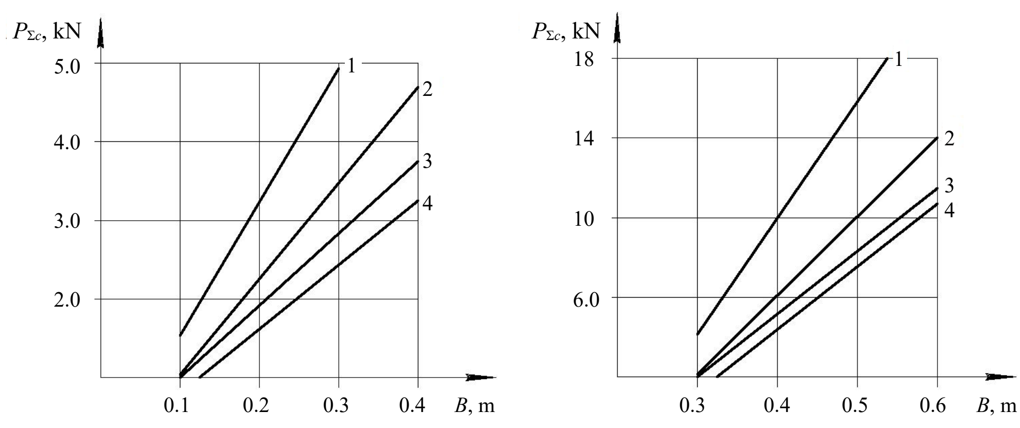

Fig. 4. Dependence of the total force of critical depth cutting of the soil on the width of the trench for the semi-blocked scheme of arrangement of cutters (soil – semi-solid clay): *a* – b_{sbl}=0.01 m; *b* – b_{sbl}=0.02 m; 1 – α_c=20°; 2 – α_c=30°; 3 – α_c=40°; 4 – α_c=50°

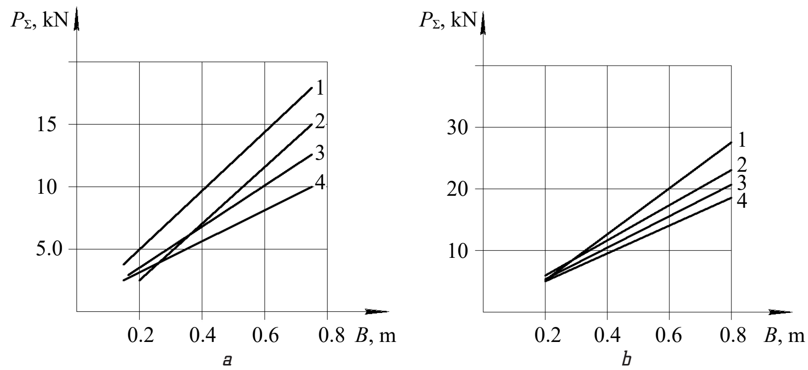

Fig. 5. Dependence of the total force of digging the soil on the width of the trench for the blocked scheme of arrangement of cutters (soil – semi-solid clay): *a* – b_{bl}=0.02 m; *b* – b_{bl}=0.03 m; 1 – α_c=20°; 2 – α_c=30°; 3 – α_c=40°; 4 – α_c=50°

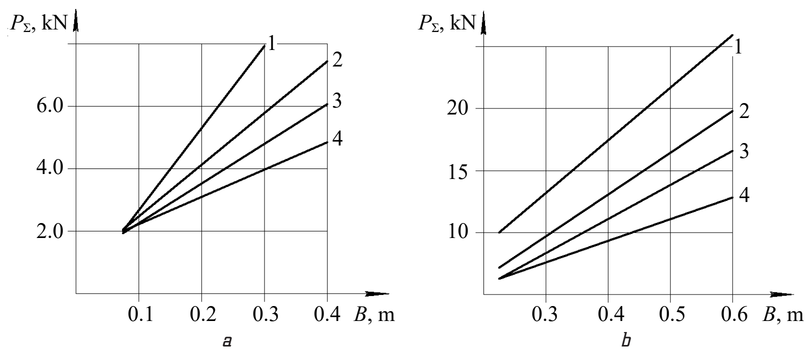

Fig. 6. Dependence of the total force of digging the soil on the width of the trench for the semi-blocked scheme of arrangement of cutters (soil – semi-solid clay): *a* – b_{sbl}=0.01 m; *b* – b_{sbl}=0.02 m; 1 – α_c=20°; 2 – α_c=30°; 3 – α_c=40°; 4 – α_c=50°

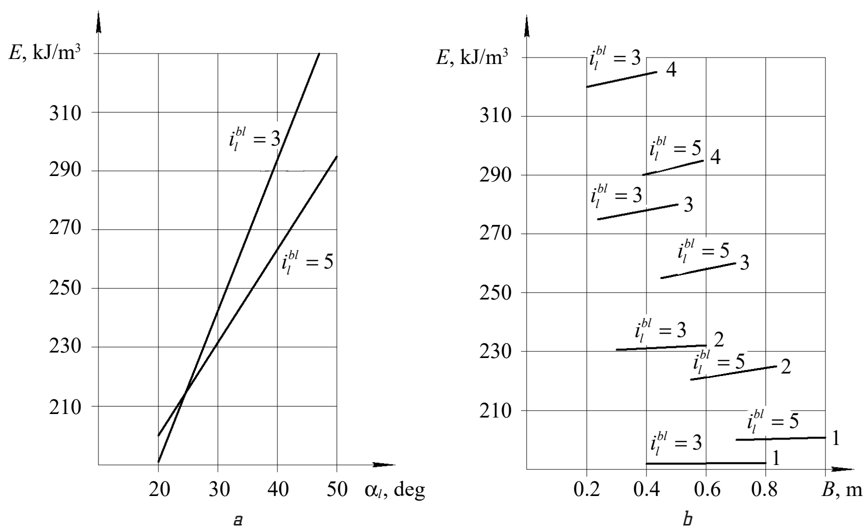

Fig. 7. Dependence of energy intensity of soil digging for the blocked scheme of arrangement of cutters on: *a* – cutting angle; *b* – trench width; 1 – α_c=20°; 2 – α_c=30°; 3 – α_c=40°; 4 – α_c=50°

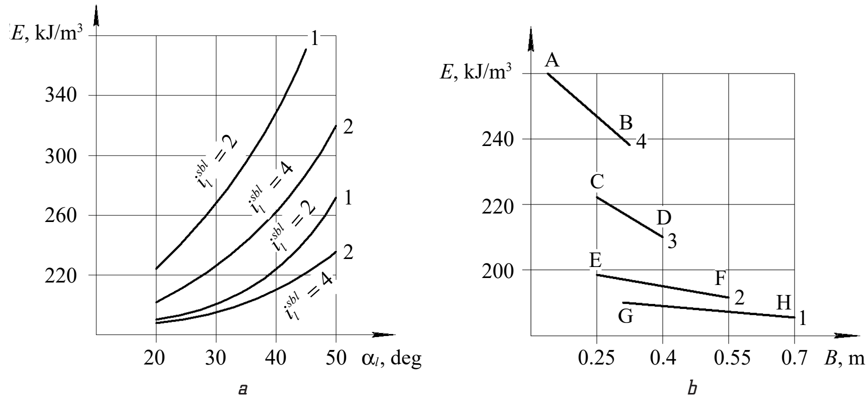

Fig. 8. Dependence of energy intensity of digging the soil for the semi-blocked scheme of arrangement of cutters on: *a* – cutting angle (1 – b_{sbl}=0.01 m; 2 – b_{sbl}=0.02 m); *b* – trench width (1 – α_c=20°; 2 – α_c=30°; 3 – α_c=40°; 4 – α_c=50°; A, C, E, G – i_l^{sbl} =2; B, D, F, H – i_l^{sbl} =4)

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It is recommended to implement the scheme of arrangement of cutters of the working body of the trench multi-scraper excavator based on critically deep semi-blocked soil cutting with cutting angles within α_c=20–30° and cutter width b_{sbl}=0.02 m, which reduces the energy consumption of the process of digging the soil on 2–18 % compared to blocked. This scheme provides a significant increase in the productivity of digging the soil, which requires a more in-depth study of the bearing capacity of the soil scrapers of the working body.

4. Conclusions

The method of analytical determination of energy performance of the working body of the chain trench excavator on the basis of the semi-blocked critical-depth mode of soil cutting is obtained.

The proposed calculation method allows determining some parameters of installation of working equipment, soil development and remote elements of the chain-scraper working body on the basis of semi-blocked critical depth regime of soil cutting and evaluating its energy performance.

The conducted energy analysis showed that it is more expedient to use a multi – scraper chain working body of a trench excavator based on a semi-blocked critical-depth regime of soil cutting with a cutting angle in the range α_c=20–30°. For example, for soil semi-solid clay with blocked cutting, cutting angle α_c=20–30°, cutter width b=0.02 m energy consumption of the working process varies within E=191–233 kJ/m^3; for semi-blocked cutting under the same conditions – E=187–191 kJ/m^3 that on 2–18 % less.

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