

Construction of fairways and reconstruction of channels using rotary-bucket dredgers and calculation of soil-collecting devices

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Abstract. Rotary bucket dredgers are used in various operations: dredging, mining, development of all types of soil. Despite their high weight, cost and complexity of construction, they are increasingly used in underwater soil development due to their versatility and high efficiency. The article presents the developed method for calculating the rotary bucket dredgers, taking into account their placement under water.

Keywords. Construction of fairways and reconstruction of channels, dredgers, soil-collecting devices, rotary bucket rippers, dredging, underwater mining.

1 Introduction

The development of the transport system is an urgent issue for every country, especially for Russia, which has the largest territory in the world. The transport system in such a large country consists of all types of transport: air, rail, road, and water, including of sea and river fleets. There are many rivers in Russia, including navigable ones. Sometimes, due to weather and climate conditions or for other reasons, the water level in rivers decreases; this is a bad factor that interferes with navigation on rivers. Therefore, maintaining the ability of vessels to pass through rivers is an important technical and economic task. Dredgers are used for dredging operations. They can be dredged [1-5] and bucket [6-11]. Such machines are used not only in fulfilling the works on deepening the bottom, but also in the construction of channels [12-14], retaining walls and piers [15, 16], bridges [14] and other objects [2, 3, 17-19], as well as in the development of all types of soil and mining. Rotary bucket dredgers are used both for dredging [20-24] and for mining operations [6, 8, 14, 15, 23, 25]. It should be noted that rotary bucket dredgers are effective in the development of various types of soil, but are complex in design, have a large mass and high cost. However, due to their versatility, such machines are increasingly being used [13-15, 19, 23, 26]. Therefore, there is a need to develop methods for calculating them. Some calculation methods are known, for example, for rotary bucket rippers used in rotary excavators [24-26]. In addition, it should be noted that it is necessary to take into account the heat losses in the pipelines of the bucket dredger

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drive systems [27-29]. The method presented in the article for calculating the rotary bucket ripper as a part of the dredger's ground intake device is performed taking into account the known methods, as well as considering the process of their immersion under water.

2 Materials and methods

The dredger is a fairly complex technical structure, which includes the achievements of various branches of technology. One of the main elements of the dredger is a rotary bucket ripper, the scheme of which is shown in Fig. 1. The rotary bucket dredger includes a rotary bucket ripper 1 with buckets 2 and knives 3, a hydraulic drive 4, a suction pipe 5, a ground receiver 6, mounted on a frame 7. Let's perform the calculation of the rotary bucket ripper, for which.

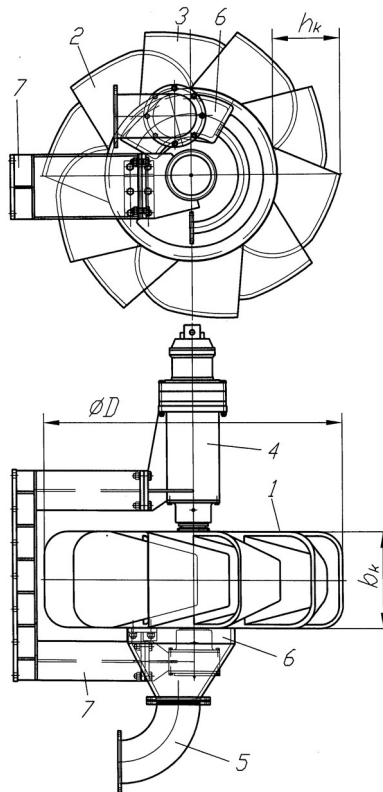


Fig. 1. Scheme of the rotary-bucket grunt intake the device of the dredger.

2.1 Define its parameters

According to the methods described in [24-26], we calculate the diameter D of the rotary ripper taking into account the location under water by the formula, m:

$$D = 0.3 \cdot \sqrt[3]{Q_{gr}} \tag{1.1}$$

where Q_{gr} – soil productivity, m^3/h .

Determine the number of z buckets on the rotor:

$$z = 4 + 0.08 \cdot \sqrt{Q_{gr}} \tag{1.2}$$

Taking into account the work [24], the number of z is taken in the range 5-9. The critical rotation speed of the n_{kr} under the conditions of gravitational unloading of the rotor under water is determined by the expression, turnovers/minute:

$$n_{kr} = \frac{30}{\pi} \cdot \sqrt{\frac{2g}{D} \left(1 - \frac{\rho_B}{\rho_{gr}} \right)}, \tag{1.3}$$

where ρ_a is the density of water, kg/m^3 , ρ_{gr} – soil density, kg/m^3 . If we take $\rho_{gr} = 2400 \text{ kg/m}^3$, then from (1.3) we get, turnovers/minute:

$$n_{kr} = \frac{32.3}{\sqrt{D}}. \tag{1.4}$$

According to [24], the rotor spinning frequency n is assumed, turnovers/minute:

$$n = (0.4 \div 0.6) \cdot n_{kr}. \tag{1.5}$$

The number of n_r offloads is determined by the formula, 1/min:

$$n_r = n \cdot z. \tag{1.6}$$

Bucket capacity q is calculated using [24], m^3 :

$$q = \frac{Q_{gr} k_r}{60 \cdot k_n \cdot z \cdot n}, \tag{1.7}$$

where k_r – is the soil loosening coefficient; k_n – is the bucket filling coefficient, $k_n = 0.9 \div 1.2$. According to [25] we accept:

$k_r = 1.3 \div 1.35$ – sand, sandy loam, light loam;

$k_r = 1.5 \div 1.55$ – loam, heavy loam, clay;

$k_r = 1.4 \div 1.45$ – shale clay, coal.

According to [25], the bucket departure h_k is defined by the expression, m:

$$h_k = \sqrt[3]{\frac{q}{k_q}}, \tag{1.8}$$

where $k_q = 0.8$ – for cohesionless soils; $k_q = 1$ – for medium-cohesive soils;

$k_q = 1.25$ – for cohesive soils.

According to the recommendations in [25], we determine the width b_k , m:

$$b_k \geq h_k. \tag{1.9}$$

2.2 We calculate the velocity V_n of papilionidae

Speed V_n of papilioninae is determined by the formula, m/min:

$$V_n = \frac{Q_{gr}}{60 \cdot F_{pl}}, \tag{2.1}$$

where F_{pl} – is the actual cross-sectional area of the papillonnage tape, m^2 . The chip height h_c and the maximum width S_{max} of the papillonnage tape (Fig. 2) can be taken in accordance with the recommendations [25], m:

$$h_c = (0.5 \div 0.7) \cdot D. \tag{2.2}$$

$$S_{max} \leq (0.7 \div 0.9) \cdot h_{kb}. \tag{2.3}$$

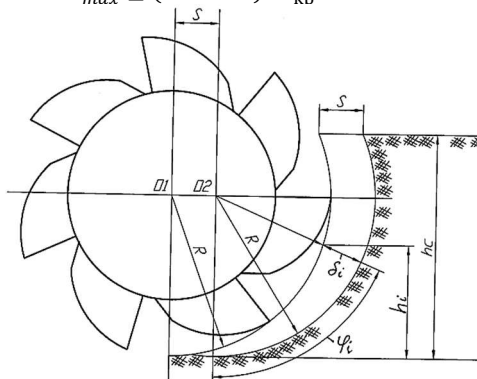


Fig. 2. Cutting scheme of the soil.

Then the area F_{pl} is defined by the expression, m²:

$$F_{pl} = h_c \cdot S, \tag{2.4}$$

where S – is the width of the papillonage tape, m. The minimum value of the speed V_n^{min} of papillonation can be calculated for $S = S_{max}$ by the expression, m/min:

$$V_n^{min} \geq \frac{Q_{gr}}{37.8 \cdot D \cdot h_k}. \tag{2.5}$$

where it is accepted $h_c = 0.7D$; $S_{max} = 0.9h_k$.

The width b_0 of the chip (Fig. 3) – the distance along the paper tape that the rotor passes in one revolution – is determined by the formula, m:

$$b_0 = \frac{V_n}{n \cdot z}. \tag{2.6}$$

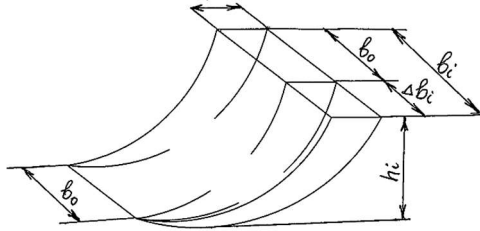


Fig. 3. The cross section of the chip.

The width b_0 of the chip should not exceed $0.9b_k$: $b_0^{max} \leq 0.9 b_k$. With this in mind, from (2.6) we get the maximum value of the papillonage speed V_n^{max} , m/min:

$$V_n^{max} \leq 0.9b_k \cdot n \cdot z. \tag{2.7}$$

The movement Δb_i of the bucket along the paper tape at the height of the chip h_i is determined by the expression, m:

$$\Delta b_i = \frac{V_n \cdot \varphi_i}{2\pi \cdot n}. \tag{2.8}$$

Then, taking into account (2.6), we can write, m:

$$b_i = \frac{V_n}{n} \left(\frac{1}{z} + \frac{\varphi_i}{2\pi} \right). \tag{2.9}$$

In the calculations, we take $h_i^{min} \geq 0,25h_k$ and receive:

$$\varphi_i^{min} = \arccos \left(\frac{R - 0.25h_k}{R} \right), \tag{2.10}$$

where $R = D/2$. Taking into account (2.5) and (2.10) for (2.9) b_i^{min} is determined.

2.3 Calculation of cutting forces

The cutting force can be represented as a tangent P_t , directed tangentially to the curve described by the scoop cutter, and normal to it P_N , which are determined taking into account the research [30], kN:

$$P_t = k_4^l \cdot f + k_5^l \cdot t \cdot l, \tag{3.1}$$

$$P_N = k_5^l \cdot t \cdot l \cdot ctg(\gamma_3 + \mu), \tag{3.2}$$

where k_4^l , k_5^l are the reduced ground shear and crumple resistances, respectively, kPa;

f – cross-section area of the ground chips to be cut, m²;

t – thickness of the blunted cutting edge of the knife, m;

l – length of the cutting edge of the scoop, m;

γ_3 – the angle of inclination of the wear pad to the path of the cutting edge of the scoop (in calculations, you can take $\gamma_3 = 17 \div 25^\circ$);

μ – the angle of external friction of the soil [31, 32].

The values of k_4^l and k_5^l in accordance with the research [31, 32] are calculated using the expressions, kPa:

$$k_4^l = k_4 \cdot \frac{\cos \rho}{\cos^2 \left(\frac{\pi}{4} + \frac{\rho}{2} \right)}, \tag{3.3}$$

$$k_5^I = k_5 \cdot \frac{\sin(\gamma_3 + \mu)}{\cos\mu}, \tag{3.4}$$

where k_4 and k_5 – are the specific resistances of the soil to shear and crumple, respectively, kPa; ρ – the angle of internal friction of the soil. According to [31, 32], the values of k_4 , k_5 , and ρ are determined depending on the type of soil.

The cross-section area of the ground chips to be cut is equal to, m²:

$$f_i = \delta_i b_i, \tag{3.5}$$

where δ_i – is the thickness of the ground chip to be cut, m; b_i – chip width, measured by the normal to the side surface of the cut, m. The value of δ_i is defined, m:

$$\delta_i = R + S \cdot \sin\varphi_i - \sqrt{R^2 - S^2 \cdot \cos^2\varphi_i}. \tag{3.6}$$

The b_i value is found by (2.9). Substituting (2.9) and (3.6) in (3.5), we get, m²:

$$f_i = \frac{V_n}{n} \left(\frac{1}{z} + \frac{\varphi_i}{2\pi} \right) \cdot \left(R + S \cdot \sin\varphi_i - \sqrt{R^2 - S^2 \cdot \cos^2\varphi_i} \right). \tag{3.7}$$

Taking into account [30] we accept, m:

$$l_i = \delta_i + b_i. \tag{3.8}$$

Substituting in (3.8) the expressions (2.9) and (3.6), we get, m:

$$l_i = \frac{V_n}{n} \left(\frac{1}{z} + \frac{\varphi_i}{2\pi} \right) + R + S \cdot \sin\varphi_i - \sqrt{R^2 - S^2 \cdot \cos^2\varphi_i}. \tag{3.9}$$

For $h_i = R$ we have $\varphi_i = \pi/2$. Then, substituting this value in (3.7) and (3.9), we find:

$$f_{90} = \frac{V_n}{n} \left(\frac{1}{z} + \frac{1}{4} \right) \cdot S, \tag{3.10}$$

$$l_{90} = \frac{V_n}{n} \left(\frac{1}{z} + \frac{1}{4} \right) + S. \tag{3.11}$$

Intermediate values of φ_i can be defined by expressions:

- if $h_i \leq D/2$, then:

$$\varphi_i = \arccos\left(\frac{R-h_i}{R}\right); \tag{3.12}$$

- if $h_i > D/2$, then:

$$\varphi_i = \frac{\pi}{2} + \arccos\left(\frac{h_i - R}{R}\right). \tag{3.13}$$

The angle α between the bucket cutters is calculated using the formula:

$$\alpha = \frac{2\pi}{z}. \tag{3.14}$$

2.4 Determine the drive power

The total power N_r of the rotor drive is found by the expression, kW:

$$N_r = N_{rez} + N_{pod} + N_{fr} + N_{zap} + N_{kin} + N_{hf}, \tag{4.1}$$

where N_{rez} – power to the cutting of soil, kW;

N_{pod} – power to the rise of ground, kW;

N_{fr} – power to overcome friction on the shut-off sector, kW;

N_{zap} – capacity for filling buckets with soil, kW;

N_{kin} – power per message to the soil that got into the bucket, kinetic energy, kW;

N_{hf} – power to overcome hydraulic resistances when the buckets flow with water and when the rotor spins under water, kW. Please note that $N_{fr} + N_{zap} + N_{kin} + N_{g.s}$ according to [25, 30] make up 2-5% of the power N_{rez} . Therefore, they can be ignored in calculations. The rotor torque when cutting soil is determined by the formula, kN m:

$$M_{kr} = \left(\sum_{i=1}^k P_v \right) \cdot R, \tag{4.2}$$

where k – is the number of cutters simultaneously involved in cutting the ground.

The cutting power of the soil is determined by the expression, kW:

$$N_{rez} = M_{kr} \cdot \omega = \frac{M_{kr} \cdot \pi \cdot n}{30}.$$

After substituting (4.2) in the above expression, we get, kW:

$$N_{rez} = \frac{\left(\sum_{i=1}^k P_v \right) \cdot D \cdot \pi \cdot n}{60}. \tag{4.3}$$

The power to lift the soil to the place of unloading the bucket, taking into account [25], is determined by the formula, kW:

$$N_{pod} = \frac{Q_{gr}}{4800} \cdot \rho_{gr} \cdot g \cdot D, \tag{4.4}$$

where ρ_{gr} is the density of soil, kg/m³; $g = 9.81$ m/s² – acceleration of free fall. The power of the rotor drive is calculated by (4.1) taking into account (4.3) and (4.4), kW:

$$N_r = 1.05 \frac{(\sum_{i=1}^k P_v) \cdot D \cdot \pi \cdot n}{60 \cdot \eta_r} + \frac{Q_{gr} \cdot \rho_{gr} \cdot g \cdot D}{4800 \cdot \eta_r}, \tag{4.5}$$

where η_r – efficiency of the rotor takes into account the friction losses in the suspension bearings (in calculations, you can take $\eta_r = 0.75 \div 0.85$).

2.5 Determine the forces acting on the rotor

The horizontal force of the P_{gd} acting on the rotor along the diameter plane of the dredger is determined by the expression, kN:

$$P_{gd} = \sum_{i=1}^k (P_v \cdot \cos \varphi_i) + \sum_{i=1}^k (P_{Ni} \cdot \sin \varphi_i). \tag{5.1}$$

The horizontal force P_{gN} acting on the rotor perpendicular to the diameter plane of the dredger is calculated by the formula, kN:

$$P_{gN} = k_5^L \cdot t \cdot ctg(\gamma_3 + \mu) \cdot \sum_{i=1}^k \delta_i. \tag{5.2}$$

Vertical force P_h acting on the rotor, kN:

$$P_h = \sum_{i=1}^k (P_v \cdot \sin \varphi_i) - \sum_{i=1}^k (P_{Ni} \cdot \cos \varphi_i). \tag{5.3}$$

The values of P_{π} and P_{Ni} are determined by (3.1) and (3.2) depending on the position of the cutting blades of the rotor buckets that are engaged with the ground.

3 Results and discussions

The calculation of the technical and economic indicators of the operation of the rotor-bucket dredger as a function of the rotational speed n of the shaft is carried out.

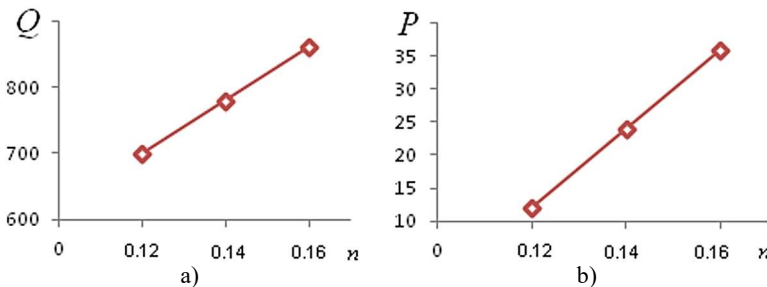


Fig. 4. Graphs of the dependence of a) performance Q and b) power P on the speed n .

Fig. 4 shows two graphs. Both dependences $Q(n)$ and $P(n)$ are linear. From the graphic it can be seen that an increase in the rotational speed n of the shaft allows increasing the productivity Q of the machine to a maximum value. The limitation of the increase in productivity Q is the power consumption P of the machine and the category of soil. In addition, the obtained dependencies allow, in specific conditions, to obtain the optimal values of technical and economic indicators for the corresponding rotational speed n of the shaft.

4 Conclusion

The proposed method for calculating a rotor-bucket dredger is an important and necessary methodological basis both when optimizing the values of the technical and economic

indicators of the dredger performance during its operation, and when performing design work during the development of new types of equipment (dredgers, excavators, etc.), used in the fulfilling of various works: dredging, mining, development of all types of soil under water. Despite their significant massiveness, high cost and design complexity, they are increasingly used in underwater excavation due to their versatility and high efficiency.

The developed calculation method was applied in the design of a rotary bucket dredger with a ground pump with a water-ground mixture of 800 m³/h in JSC «Tsimlyansky ship-mechanical plant».

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