

# Calculation of energy expenses for moving soil by the conveyor of the unit for tunneling

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**Abstract.** Russia has a large spatial separation of settlements and other objects. Therefore, the construction of highways using technical means of cyclic action is inefficient. The use of a complex of continuous units will increase the pace of road construction, improve their quality and reduce energy costs. All units of continuous operation are patented in Russia. They allow you to perform the entire complex of road construction works by the flow method. The complex includes a tunneling unit for open and closed excavation, taking into account terrain irregularities. The proposed tunneling unit allows the development of tunnels with a width of 4.3 m and a height of 3.4 m using direct-flow rotary rippers, augers and passive knives. The calculation of the main parameters of the tunneling unit conveyor drive is carried out. The theoretical capacity of the tunneling unit, in the absence of rocky and frozen soil, in terms of the volume of undrafted soil was 1.054 m<sup>3</sup>/s. As a result of calculations, the total energy costs for moving one cubic meter of soil amounted to 38218 J/m<sup>3</sup>. The estimated power of the conveyor drive (excluding idling) was 52 kW. The torque of the conveyor drive is 936 Nm.

## 1 Introduction

Russia has a large spatial separation of settlements, unlike many other countries of the world. Therefore, the use of technical means of cyclic action in the construction of highways is not effective. The use of continuous-acting aggregates makes it possible to increase the pace of

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road construction, improve their quality and reduce energy costs during the construction of highways. Therefore, their use is economically feasible wherever the terrain allows [1-2].

Units of continuous operation can carry out the construction of a highway by a flow method, moving one after another and consistently performing the entire complex of necessary works [3]. It is advisable to use such a complex of aggregates not only in Russia, but also in other countries where the problem of highways is relevant.

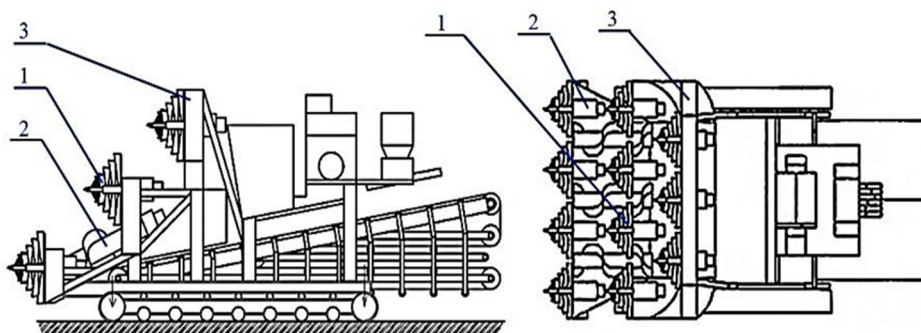
The designs of the units of the complex are patented in Russia:

- Tunneling unit (Patent RU 2765746).
- Unit for soil removal from underlying layer of motor road (Patent RU 2689007).
- Unit for the installation of wells (Patent RU 2758855).
- Straight-flow rotary ripper (Patent RU 2735497).
- Continuous action unit forming cuvette and base of motor road (Patent RU 2709849).
- The device for forming the foundation of highways (Patent RU 2766852).
- Unit for performing a complex of works on the device of curbs of highways (Patent RU 2777314).
- Unit for laying paving slabs (Patent RU 2740596).
- Device for laying asphalt and marking roads (Patent RU 2790915).
- Bulldozer equipment (Patent RU 2770854).
- Material separator (Patent RU 2740983).
- Internal combustion hydraulic motor (Patent RU 2774925).
- Advanced bulldozer equipment (Patent RU 2770854).

The use of a complex of continuous units will allow the construction of highways in automatic mode.

The unit for tunneling is included in the complex for overcoming terrain irregularities. Tunneling machine is a shield with a head section equipped with destructive elements on a rotating spindle. The tunnel in this case has a round profile [4-5]. The disadvantage of the tunneling unit is the large energy costs for the destruction of the soil [6-8].

We offer tunneling unit (Patent RU 2765746), allowing the development of tunnels with a width of 4.3 m and a height of 3.4 m using direct-flow rotary rippers, augers and passive knives (Figure 1).



**Fig. 1.** Tunneling unit for tunneling 4.3 m wide and 3.4 m high (1 is direct-flow rotary ripper; 2 is auger; 3 is passive knife).

The tunneling unit frame is supported by a tracked undercarriage. Rows of direct-flow rotary rippers 1 are mounted on the frame of the unit and are offset in height. Three augers 2 and eight passive knives 3 are installed on the frame. This combination of working bodies allows you to reduce energy costs for soil destruction at a higher tunnel penetration rate.

When moving the unit, the lower passive knives cut the ground. The lower row of ramjet rotary rippers loosens the soil within the future tunnel. The soil enters the conveyor belt by means of augers. The augers loosen the lintels between the direct-flow rotary rippers of the lower row.

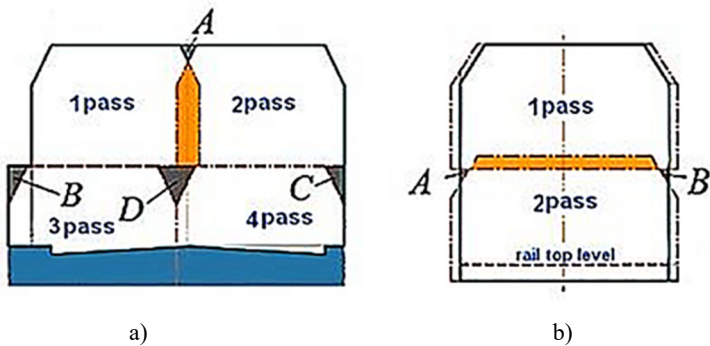
Ramjet rotary rippers of the middle and upper rows, upper and side passive knives gradually loosen the soil and direct it to the conveyor. At the same time, a significant part of the soil falls on the conveyor without the impact of direct-flow rotary rippers. The soil from the conveyor is sent to the vehicle.

The drive of all elements of the tunneling unit is hydraulic. Pumps driven by the engine create the pressure of the working fluid. Some pumps outside the tunnel supply waterproofing. Other pumps supply a solution to strengthen the walls of the tunnel. Passive knives at the same time serve as a sliding formwork.

Fans play an active role. Some fans suck out the exhaust gases. Other fans pump air into the engine's water-air heat exchanger. The air passes through the water-air heat exchanger and enters the surface of the solution, which contributes to its rapid hardening. This air heats the tunnel space and creates excessive pressure in it. The presence of water-air and gas-air heat exchangers increases the efficiency of the engine.

Hydraulic cylinders control the position of the passive knives. The pressure gauge in the operator's cabin shows the pressure in the hydraulic drive of the chassis. This pressure reflects the difference between the total longitudinal force generated by eleven ramjet rotary rippers and the total resistance of passive knives. The control and alarm unit controls the position of the passive knives depending on the pressure in the hydraulic drive of the chassis. Passive knives can rotate and change the sealing of the walls and arch of the tunnel. If necessary, the operator can also control the position of the passive knives.

The proposed tunneling unit design allows for the laying of a category IV highway tunnel designed for two-lane traffic of cars in four passes and for the laying of a railway tunnel for one track in two passes (Figure 2).



**Fig. 2.** Tunneling unit sinking scheme: (a) Category IV highway (GOST 24451-80); (b) railway tunnel (GOST 9238-13).

When laying an automobile tunnel, there is an overlap of the first and second penetrations (orange color on Figure 2a). The blue color shows the selected soil for the subsequent formation of the road base. At the same time, sections *A*, *B*, *C* and *D* remain not passed. Their area occupies a significant proportion of the total cross-section of the tunnel. The collapse of the tunnel arch in sections *A*, *B* and *C* occurs with the help of an additional passive working body. Section *D* collapses during the third and fourth sinking.

When laying a railway tunnel using the tunneling unit, it turns out to be slightly wider than the one provided by GOST (dashed line on Figure 2b). The overlap of the first and second penetrations is shown in yellow when laying a railway tunnel (Figure 2b). At the same

time, sections A and B remain not passed. Their area is a small fraction of the total cross-section of the tunnel. An additional passive working body is used to collapse these sections.

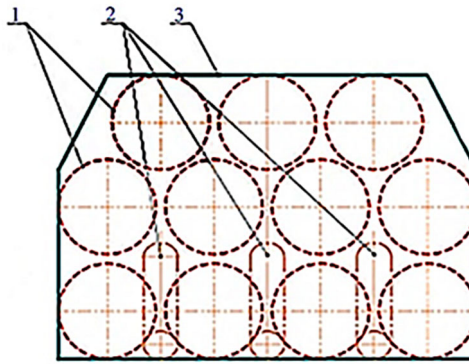
Theoretical calculations of the parameters of the working bodies are necessary for the rational organization of the tunneling process.

**The purpose of the study** is to calculate the energy costs of the conveyor drive and the required drive power.

## 2 Materials and methods

To calculate the required power of the conveyor drive, it is necessary to calculate the horizontal force necessary to move the soil.

To do this, consider the layout of the working bodies of the tunneling unit (Figure 3).



**Fig. 3.** Layout of the tunneling unit working bodies: 1 is ramjet rotary ripper; 2 is auger; 3 is passive knife.

Eleven direct-flow rotary rippers 1 with a diameter of  $d = 500 \text{ mm}$  is designed for loosening the soil. Augers 2 extract the soil from the gaps between the lower rippers. Passive knives 3 form the profile of the penetration.

The total cross-sectional area of the penetration is  $S_{\Sigma} = 12.4 \text{ m}^2$ . The area developed by eleven rotary rippers is [9]

$$S_{11r} = 11 \frac{\pi D^2}{4} = 8.635 \text{ m}^2.$$

The cross-sectional area of the soil treated with three augers, excluding overlap with a direct-flow rotary ripper, is

$$S_{3s} = 3S_s = 0.882 \text{ m}^2,$$

where  $S_s = 0.294 \text{ m}^2$  is the cross-sectional area of the soil processed by a single screw without taking into account overlap with a ramjet rotary ripper is equal to.

The area loosened by passive knives and the area of spontaneous collapse is equal to

$$S_k = S_{\Sigma} - S_{11r} - S_{3s} = 2.883 \text{ m}^2$$

and accounts for 23.25% of the total cross-sectional area of the sinking developed by tunneling unit.

The throughput of the  $Wu$  tunneling unit is determined by

$$W_u = S_{\Sigma} v_u = 1.054 \text{ m}^3/\text{c},$$

where  $v_u = 0.085 \text{ m/s}$  is the speed of the tunneling unit.

The longitudinal force generated by eleven direct-flow rotary rippers and contributing to the movement of the unit is equal to

$$R_{\Sigma r} = 11 R_r = 214\,577 \text{ N},$$

where  $R_r = 19\,507 \text{ N}$  is longitudinal force of one direct-flow rotary ripper [10].

Passive knives are mounted pivotally. They separate the developed soil from the massif and seal the soil of the walls and arch of the tunnel. The total strength of the ground resistance to the movement of passive knives is equal to

$$R_{\Sigma k} = cL\tau_k = 221\,376\text{ N},$$

where  $c = 20\text{ mm}$  is the depth of loosening of passive knives;  $L = 13\,836\text{ mm}$  is the length of the tunnel perimeter;  $\tau_k = 0.8\text{ MPa}$  is the resistance of the soil to the movement of one passive knife, taking into account the sealing of the walls and arch of the tunnel [11-12].

The longitudinal resistance force of the direct-flow rotary ripper almost overcomes the resistance of the ground to the movement of passive knives:

$$R_{11r} = R_{\Sigma k} - R_{\Sigma r} = 6\,819\text{ N}.$$

The throughput of the tunneling unit, taking into account the loosening of the soil, is equal to

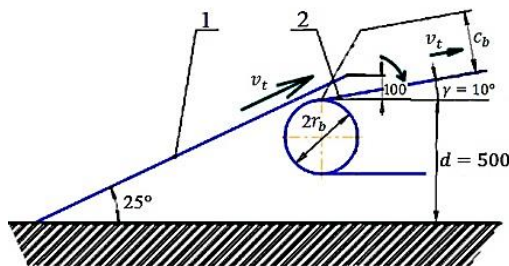
$$W_{ur} = W_u k_r. \quad (1)$$

where  $k_r = \rho_r/\rho$  is coefficient that takes into account the increase in the volume of soil as a result of its loosening;  $\rho_r = 1230$  is the density of loosened soil;  $\rho = 1600$  is the density of undrawn soil [13].

The capacity of the unit by the mass of the soil

$$W_{um} = W_{ur} \rho_r. \quad (2)$$

The lower slope is inclined to the horizontal at an angle  $25^\circ$  (Figure 4).



**Fig. 4.** Diagram of the lower slope (1) and conveyor (2) tunneling unit.

The soil slides along the lower slope under the pressure of the loosened soil. From the lower slip, the soil falls onto the conveyor belt and is distributed evenly. The speed of the soil relative to the conveyor belt is zero. The speed of the conveyor is equal to

$$v_t = W_{ur}/b_t c_b, \quad (3)$$

where  $b_t$  is width of the conveyor web;  $c_b$  is height of the conveyor sides.

The angular velocity of rotation of the drum driving the conveyor is equal to

$$\omega_b = v_t/r_b, \quad (4)$$

where  $r_b$  is радиус ведущего барабана транспортера.

Energy costs are required to move the soil by the conveyor:

- to accelerate the ground;
- to move it horizontally;
- to lift the ground vertically.

## 2.1 Energy costs for soil acceleration

Energy costs for acceleration of one cubic meter of soil

$$U_a = a_g m_g S_g, \quad (5)$$

where  $a_g$  is acceleration of the conveyor;  $m_g$  is mass of one cubic meter of loosened soil;  $S_g$  is the distance that the soil will overcome from the beginning of its arrival on the conveyor belt to the exit from the conveyor.

The acceleration of the conveyor is equal to

$$a_g = (v_t - v_0)/t_1, \quad (6)$$

where  $v_t$  is the final speed of the conveyor;  $v_0 = 0$  is the initial speed of the conveyor;  $t_1 = 1/W_{ur}$  is acceleration time.

## 2.2 Energy costs for moving the soil horizontally

Energy costs for moving one cubic meter of soil along the conveyor

$$U_{gx} = F_f S_g, \quad (7)$$

where  $F_f$  is the force of overcoming friction in the conveyor rollers;  $S_g$  is the length of soil transportation along the conveyor.

The force for moving the soil horizontally on the conveyor belt is equal to

$$F_g = f m_g g, \quad (8)$$

where  $f$  is coefficient of friction in the conveyor rollers;  $g = 9,81 \text{ m/c}^2$  is acceleration of gravity;  $m_g = t_2 W_{um}$  is mass of soil on the conveyor belt;  $t_2 = S_g/v_t$  is time of movement of the soil particle on the conveyor belt.

## 2.3 Energy costs for lifting the soil vertically, total energy costs

The energy cost of lifting one cubic meter of soil vertically is equal to the potential energy of the system

$$U_{gy} = g m_g h_t, \quad (9)$$

where  $h_t$  – ground lifting height by conveyor.

## 2.4 Total energy costs for moving one cubic meter of soil by a conveyor

$$U_{\Sigma} = U_a + U_{gx} + U_{gy}. \quad (10)$$

The drive power of the conveyor without taking into account the energy costs of idling

$$N = U_{\Sigma}/(t_1 + t_2). \quad (11)$$

The torque of the conveyor belt drive is equal to

$$M_t = N/\omega_b. \quad (12)$$

The gear ratio of the conveyor drive gearbox is equal to [14]

$$i = \omega_d/\omega_b, \quad (13)$$

where  $\omega_d$  – angular velocity of the internal combustion engine.

## 3 Results and discussion

The throughput of the tunneling unit at a speed of  $v_u = 0.085 \text{ m/s}$  is  $W_u = 1.054 \text{ m}^3/\text{s}$  of undrafted soil.

A coefficient that takes into account the increase in the volume of soil as a result of its loosening  $k_r = 1.3$  [13].

Then the throughput of the tunneling unit, taking into account the loosening of the soil (1), is equal to

$$W_{ur} = 1.054 \cdot 1.3 = 1.37 \text{ m}^3/\text{s}.$$

The capacity of the tunneling unit by ground weight (2) is

$$W_{um} = 1.37 \cdot 1\,230 = 1\,686 \text{ kg/s}.$$

The lifting height of the soil along the lower slope is  $0.6 \text{ m}$ . From the lower slope, the soil falls onto the conveyor belt. The width of the conveyor belt  $b_t = 2.9 \text{ m}$ . The height of the conveyor sides is  $c_b = 0.25 \text{ m}$ . The angle of inclination of the conveyor to the horizon  $\gamma =$

10° (Figure 4). The lifting height of the soil by the conveyor is  $h_t = 1.76 \text{ m}$ . The length of soil transportation by conveyor  $S_g = 10 \text{ m}$ .

Calculate the speed of the conveyor (3)

$$v_t = 1.37/2.9 \cdot 0.25 = 1.889 \text{ m/s}$$

Round the conveyor speed to  $v_t = 2 \text{ m/s}$ .

The radius of the drive drum of the conveyor  $r_b = 0.15 \text{ m}$ . Then its angular velocity (4) is equal to

$$\omega_b = 2/0.15 = 13.3 \text{ s}^{-1}.$$

### 3.1 Energy costs for soil acceleration

The acceleration time of one cubic meter of soil at the conveyor capacity  $W_{ur} = 1.37 \text{ m}^3/\text{s}$  is  $t_1 = 0.73 \text{ s}$ .

Ground acceleration (6) is equal to  $a_g = 2/0.73 = 2.74 \text{ m/s}$ .

Energy costs for acceleration of one cubic meter of loosened soil (5) are  $U_a = 2.74 \cdot 1230 \cdot 1.46 = 4925 \text{ J/m}^3$ .

### 3.2 Energy costs for moving the soil horizontally

The time of moving the soil along the conveyor is  $t_2 = 5 \text{ s}$ . Tunneling unit throughput by ground weight  $W_{um} = 1.37 \cdot 1230 = 1686 \text{ kg/s}$ . The mass of the soil on the conveyor belt is  $m_g = 5 \cdot 1686 = 8430 \text{ kg}$ .

With the coefficient of friction in the conveyor rollers  $f = 0.1$  the force required to move the soil along the conveyor belt (8) is equal to

$$F_g = 0.1 \cdot 9.81 \cdot 8430 = 8261 \text{ N}.$$

The energy costs for moving one cubic meter of soil horizontally (7) are equal to

$$U_{gx} = 8261 \cdot 1.46 = 12061 \text{ J/m}^3.$$

### 3.3 Energy costs for lifting the soil vertically, total energy costs

Energy costs for lifting one cubic meter of soil vertically (9) are equal to

$$U_{gy} = 9.8 \cdot 1231 \cdot 1.76 = 21232 \text{ J/m}^3.$$

### 3.4 Total energy costs

Total energy costs for moving one cubic meter of soil by a conveyor (10)

$$U_{\Sigma} = 4925 + 12061 + 21232 = 38218 \text{ J/m}^3.$$

The drive power of the conveyor (11) is equal to

$$N = 38218/0.73 = 52353 \text{ W} \approx 52 \text{ kW}.$$

The energy cost of idling the conveyor is 10% of the energy cost of transportation. The drive power of the conveyor, taking into account the energy consumption at idle, is equal to  $N = 52 \cdot 1.1 = 57 \text{ kW}$ .

The rotating moment of the conveyor drive (12) is equal to

$$M_t = 52353/13.3 = 3936 \text{ Nm}.$$

According to the calculation, a high-torque radial piston hydraulic motor MRF-630/25 M was selected for the conveyor drive. Its rated power is 70 kW. Its rotating moment is 2,276 Nm at a nominal rotor shaft speed of 300 rpm. Hence, the angular frequency of the motor  $\omega_d = 31.4 \text{ s}^{-1}$ .

Gear ratio of the conveyor drive gear stage (13)

$$i = 31.4/13.3 = 2.36.$$

The actual moment on the drive shaft of the conveyor was

$$M_t = 2\,276 \cdot 2.36 = 5\,371 \text{ Nm}.$$

The rotating moment reserve is provided.

## 4 Conclusions

The use of a complex of continuous-action aggregates makes it possible to increase the efficiency of road construction in automatic mode. The complex of aggregates includes a tunneling unit for open and closed excavation, taking into account the irregularities of the relief. The tunneling unit design is proposed, which allows the development of tunnels with a width of 4.3 m and a height of 3.4 m using direct-flow rotary rippers, augers and passive knives.

The calculation of the main parameters of the tunneling unit conveyor drive is carried out. The theoretical throughput of the tunneling unit in the absence of rocky and frozen soil is: by volume of undrafted soil  $W_u = 1.054 \text{ m}^3/\text{s}$ , by mass of soil  $W_{um} = 1\,686 \text{ kg/s}$ .

One of the elements of the unit for tunneling is a conveyor. As a result of calculations, the total energy costs for moving one cubic meter of soil by the conveyor  $U_\Sigma = 38\,218 \text{ J/m}^3$ .

The power required to drive the conveyor, excluding energy costs for idling, was  $N = 52 \text{ kW}$ .

The calculated rotating moment of the conveyor drive was  $M_t = 3\,936 \text{ Nm}$ . To realize such a rotating moment, it is recommended to use a chain drive.

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