Design Improvement of Cutting Part in Tunneling Shield

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Abstract. The article presents a variant for improving the design of a working body of a tunneling shield, its cutting part to be more precise. The working body of the tunneling shield has been improved with the changes in the design of a rotor working surface. The theoretical studies aimed at determining the strength characteristics of the proposed rotor design have been carried out. The proposed rotor model has been visualized with the use of the T-Flex CAD software. On the basis of the results obtained in the course of the theoretical research, a comparative analysis of the strength characteristics of the main and improved model of the cutting working body of the tunneling shield have been made. The studies carried out at T-Flex CAD confirmed the working capacity of the improved design of the tunneling shield working body. The strength of the rotor has been determined as a result of the studies carried out. The maximum values of the displacement module is 2.875×10^{-5} m, the equivalent stresses are 29.47 MPa, a reserve coefficient on equivalent stresses is 9.446×10^6 .

1 Introduction

A tunneling shield is a prefabricated mobile metal structure, the function of which ensures the safety of tunneling works and the assembly of the permanent support (lining) of the tunnel [1]. A tunneling shield is essential in construction works for building tunnels of any purpose. The machine is used for underground mining and for construction of tunnels of various purposes [2]. The diameter of the tunnels obtained with the tunneling shield may vary from 1 to 19 metres.

The use of this machine makes it possible to implement the trenchless method of pipeline with a mechanical method in both watered and dry soils without a human involvement in a bottom [3]. The trenchless method of pipeline is considered promising and can simultaneously achieve the following:

1. Construction of underground utility lines (water, heat, gas, sewage);
2. Construction of electric cable cases [4];
3. Construction of runways, railways and motorways;
4. Construction of feeding structures to the objects located at the centre of the water body [1.4];
5. Original support for large tunnels [4].

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2 Purpose of research

3 Research material and methods

Technical drawing of a circular machine component, likely a rotor or stator assembly. The drawing includes a top view and a cross-sectional view labeled A-A.

Top View:

- The component is circular with a central hub and eight radial arms.
- The central hub features a circular array of holes and a central slot.
- The radial arms are arranged in a star-like pattern.
- Dimensions: The overall diameter is 650.3.
- Section line A-A is indicated at the top and bottom.
- Labels 1, 2, and 3 point to specific features: 1 points to a radial arm, 2 points to a central hub feature, and 3 points to a central slot.

Cross-sectional View A-A:

- This view shows the internal structure and dimensions of the component.
- Dimensions: The total height is 650.3. The central slot width is 65.0. The outer diameter is 650.3. The inner diameter is 460.3.
- Labels 4, 5, and 6 point to specific features: 4 points to a central hub feature, 5 points to a radial arm, and 6 points to a central slot.

The cutting element of the working body of the tunneling shield consists of a cutting head of the shield (1), cutting elements (2) which are arranged in the form of rockers along the whole area of the working surface, roller cutters (3), a shell (4), a rear cover (5) and rear cover supports (6).

The design of the basic working body is improved by the fact that the central element of the working surface of the rotor is projected. A borer [6] is fixed to the working surface in the form of a crosspiece with cutting elements arranged at the ends of it. The cutting elements arranged at an angle to each other are in the form of the hard alloy inserts. Each cutting element on the working surface of the rotor is in the form of a rocker. The remaining working surface of the rotor is provided with the slotted tools.

In order to confirm the efficiency of the proposed idea of the cutting part of the tunneling shield, some calculations are carried out to determine the movement forces of the shield, as well as the calculations aimed at determining power and torque.

The forces which the tunneling shield overcomes during the movement are the resistance force to the penetration of the head into the bottom, the friction force on the rock with the outside surface of the shell, the friction force of the inside surface of the shell on the erected lining, and the part of the tunneling complex that moves with it.

Under these conditions, the rated force of the shield shift is determined with the formula [7,8].

$$Fr = F_1 + F_2 + F_3 + F_4, \quad (1)$$

where F_1 is the frontal resistance of the head of the shield, kH; F_2 is the resistance to the shift along the outside surface of the shield shell, kH; F_3 is the resistance to the shift along the inside surface of the shield cover, kH; F_4 is the displacement force of a part of the tunneling technological complex, kH.

$$F_1 = p_{sp} \cdot D \cdot \pi, \quad (2)$$

where p_{sp} is a specific penetration force equal to 1200 1600 kH/m² in loams; D is the shield diameter, m.

$$F_2 = f_m \cdot [2 \cdot (1 + \xi) \cdot q \cdot L_m \cdot D + G], \quad (3)$$

where f_m is the coefficient of soil friction on steel, 0.80 - 0.95; ξ is a lateral pressure coefficient of rock (clay soils depending on density and composition, $\xi = 0.30 - 0.85$); q is the intensity of vertical rock pressure on the shield, n/m²; G is the mass of the shield, t.

If the depth of the tunnel is relatively large when a collapsed structure is formed above the shield, the intensity of the vertical rock pressure [9]

$$q = \gamma \cdot h, \quad (4)$$

where γ is the average mass of the rock above the shield, t/m³; h is the height of the collapse vault, m.

The height of the roof arch is determined with the formula [10, 11]

$$h = \frac{B}{2f}, \quad (5)$$

where B is a span of the pressure arch, m; f is a coefficient of rock hardness according to Professor M.M. Protodiakonov's scale.

The span of the pressure arch is determined according to Professor M.M. Protodiakonov's theory [12]

$$B = D + 2 \cdot D \cdot \tan(45 - \frac{\varphi}{2}), \quad (6)$$

where φ is the angle of internal friction, deg.

In order to press the concrete mixture under the shield shell in the longitudinal direction at the initial shift of the shield, the value of the force will be maximum. The force value is determined by considering the equilibrium of the elementary volume of the mixture between the formwork and the shield shell under the pressure produced by a pressure ring.

The formula [13] is applicable in the case of the use of a shifting sectional formwork

$$F_3 = \rho_0 \cdot \pi \cdot R \cdot (R - r) \cdot (1 - \exp(-\frac{2 \cdot \mu \cdot f_2 \cdot L}{R - r})) \quad (7)$$

where ρ_0 is the axial pressure on the concrete mixture under the end of the pressing ring, H/m²; R is an inside radius of the shield shell, m; r is an outside radius of the

formwork, m; μ is a lateral pressure transmission coefficient in the concrete mixture; f_2 is a metal friction coefficient on the concrete mixture; L is the length of the space under the shield shell filled with concrete mixture, m.

$$F_4 = G_1 \cdot f_2 \cdot k, \quad (8)$$

where G_1 is a mass of the part of the tunneling complex moving along with the shield, t; k is a coefficient considering a possible local resistance to the movement of the tunneling complex elements.

The power required for the development of the soil depends on a defined productivity of the shield, its diameter and the resistance of the soil to the destruction.

For shields with a cutter wheel the power (kW) spent on soil development [14,15]

$$N = \frac{2 \cdot \pi \cdot M_{tor} \cdot n_{ff}}{\eta}, \quad (9)$$

where M_{tor} is a torque on a shaft of a cutter wheel, kH/m; n_{ff} is a frequency of a rotational speed of a cutter wheel, c^{-1} ; η is a drive efficiency equal to 0.85-0.9.

The torque of a cutter wheel [9,14]

$$M_{tor} = (1.2 \div 1.5) \cdot \frac{\pi}{1.2} \cdot f_{fr1} \cdot p_1 \cdot D_{ex}^3, \quad (10)$$

where the multiplier 1.2 considers the costs for cutting and loading the soil (refers to the sands development); 1.5 are for clays and loams; f_{fr1} is a coefficient of soil friction on steel; p_1 is a horizontal soil pressure, MPa; D_{ex}^3 is a diameter of a cutter wheel, m.

4 Research findings and discussions

The theoretical research aimed at determining the strength characteristics of the proposed design of a working body of a tunneling shield was carried out in the T-Flex CAD software product. The applied automated design system has sufficient means to develop projects of any difficulty, besides it combines a wide range of parametric possibilities for 2D and 3D modelling.

The following algorithm is included in the strength calculations:

1. Set the material and determine the type of attachment for the cutting part of the tunneling shield (heat-resistant stainless steel of 20x13 chromium grade, which is distinguished with its resistance to mildly aggressive media, is used for the product).
2. Set the load (the forces arising on the cutters of the shield are determined with the formula (2); the forces are applied to the attachment points of the cutters on the rotor of the tunneling shield; the forces are directed along the axes of the cutters).
3. Construct a mesh in a solid that breaks the model into smaller segments.
4. Calculate the displacement module.
5. Calculate the equivalent stresses.
6. Calculate the reserve coefficient for the equivalent stresses.

Figure 2 shows the visualization of the theoretical studies results to determine displacements in the structure of a working body of the tunneling shield in a basic (2a) and improved parts (2b).

Fig.2. Study of displacements in the structure of the cutting element of the working body:
a. basic design; b. improved design.

The results of the studies showed that the minimum movements in both the basic and the proposed model occur at 0 mm. At the same time, the maximum movements in the basic model of the cutting element of a working body occur at 3.423e-05 m, in the developed - at 2.875e-05 m. Figure 3 presents the results of the studies aimed at determining possible stresses in the design of the cutting element of a working body [16,17].

Fig. 3. Study of stresses in the structure of the cutting element of the working body: a. - basic design; b. - modernized design.

The studies have concluded that the minimum values in the basic model design are equal to 6.661E-06 MPa and the maximum values are equal to 26.04 MPa. In the proposed model the minimum is 5.029E-05 MPa and the maximum is 29.47 MPa.

Figure 4 presents the results of the studies aimed at determining a reserve coefficient in the cutting element of the working body in the basic and improved models [18,19].

Fig. 4. Study of strength in the structure of the cutting element of the working body:
a. basic design; b. modernized design.

A reserve coefficient for the equivalent stresses of the basic model is 7.528 MPa minimum, the maximum values are 2.942E 07. The safety factor of a improved design is 1 with the minimum values and 9.446E 06 with the maximum values.

5 Conclusion

The article proposes the model of the structural modifications in a cutting part of a tunneling shield. The calculations carried out using T-Flex CAD software proved the working capacity of a cutting wheel. The stresses obtained during the calculation of a rotor design does not exceed the accepted values of yield strength of steel. The results of the research led to the conclusion that the proposed model of the design of a working body of a tunneling shield was used reasonably and efficiently. The results of the calculations presented need to be further validated in the course of the pilot studies.

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