Research of sparing technologies of tunneling

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Abstract. In the work, various tunneling technologies were considered. Separately analyzed force factors and torque. The axial and radial forces acting on the breed arising in the presence of a conical part of the tool are estimated. Three ways to balance the torque are considered. A moments alignment device is described for a method by dividing a penetration zone into annular and circular parts. As a criterion for the choice of technology, it is proposed to use the indicator of the stress-strain state that occurs at the time of penetration, calculated in accordance with the theory of the highest tangential stresses. The study of four different tunneling technologies by the selected criterion showed that they can be ranked by the created stress-strain state. At the same time, the generated stresses are affected not only by the driving conditions in the form of axial force and torque, but also by the presence and size of the conical part of the tool, as well as torque equalization devices. The smallest stresses in the rock are created with direct selection technology, since there is no torque, and due to local selection with a small tool, the axial pressure decreases. In second place in preference is the technology with equalization of moments, however, it is based on a rather complex technical device. The largest load on the breed is provided by the shield technology of sinking due to the simultaneous presence of both axial force and torque.

1. Introduction

The tunnels are multi-purpose, so there is a steady need for them, despite the high cost of construction. In the future, in connection with the plans for the development of other planets, this need will only increase.

The most difficult thing is to build a tunnel in difficult engineering and geological conditions, in weak or semi-fractured breeds, especially provided that the work performed is highly efficient and safe [1]. This situation very often arises in the construction of transport, sewer and hydraulic tunnels in dense urban areas, when high stresses in already loaded rocks are unacceptable. It is clear that in such conditions it is necessary to apply “gentle”(sparing) mining technology, that is, with a reduced load on the surrounding breed in the bottomhole zone.

There are technologies that make it possible to provide the necessary performance even in adverse mountain-geological conditions. Such technologies include special methods of penetration. They suggest either a temporary change in the properties of the soil by freezing, lowering the groundwater level or driving under compressed air. Or, the strengthening of soil properties over a long period of time, carried out by injecting cement slurries into the voids and cracks of the rock mass surrounding the tunnel. Cement slurries are used here for cementation, claying, bituminization, resinization and silicatization, and ultimately for monolithization and soil consolidation. The required result can be achieved by drilling wells and injecting solutions into the backfill space. However, additional work leads to an increase in
the cost of construction and, moreover, more often than not, it still requires a reduction in the stress-strain state of the rocks surrounding the tunnel due to a decrease in penetration rates. We are investigating how to reduce the driving load by technological means.

2. Theory
When driving tunnels of circular cross section, which in practice most often occurs, two types of loads on the surrounding rock arise: force loads and torsion loads. Since they are weakly connected with each other, we will conduct a separate study of their influence.

In the absence of rotational movement, the tool is pressed into the breed by axial force along the axis of the tunnel and spreads the breed in the radial direction (wedge effect), so it is logical to divide these effects into equal shares. A diagram of this effect in the form of an axial section of the tunnel is shown in Figure 1.

![Figure 1](image1)

**Figure 1.** Scheme of force impact on the breed during tunneling.

Along the axis of the tunnel, the force $F$ acts on the tool. Laying it out on the upper and lower components, we understand that to fulfill the condition of equal load along the axis of the tunnel and in the radial direction, an angle $\psi$ of forty-five degrees is necessary. However, further decomposition of the force already on the conical wall of the face ($N$ is the normal reaction of this wall, $F_{tr}$ is the friction force) shows that this angle must be increased to maintain the equality of the axial and radial components of the load. This is due to the deviation of the resulting force $T$ by the angle $\alpha$ due to the arising friction force of the tool on the rock. It is no coincidence that a similar angle $\psi$ at the drill, a tool for making holes in materials, the design of which has been worked out over the centuries of human practice, is $50 \ldots 55^\circ$ [2]. In tunneling shield machines, however, where the shield simultaneously serves as a protection against collapse of the face, this angle can reach $90^\circ$ [3,4].

From geometry it follows that the axial and radial components are respectively equal

$$F_{as} = F$$  \hspace{1cm} (1)
$$F_R = \frac{F \cos(\psi + \alpha)}{2 \sin(\psi + \alpha)}$$  \hspace{1cm} (2)
$$\alpha = \arctg(f)$$  \hspace{1cm} (3)

Here $f$ is the coefficient of friction of the tool on the rock. It must be remembered that if the angle $\psi$ is less than or equal to the angle $\alpha$, the axial load falls into the so-called friction cone [5] and the rock sliding along the tool ceases, and the friction force starts to change up to zero at $\psi = 0$. 

The rotational movement of the tool, on the one hand, is very technological, but, on the other hand, imposes a torque on the surrounding rock that shifts its layers, which is sometimes more dangerous than the pressing effect.

The simplest idea is to remove the torque by rotating two parts of the tool (circular and annular) in different directions [6]. A transverse section of the tunnel in the near-wellbore area with such a tunneling technology is shown in Figure 2.

\[ M_1 = \int_0^R Prdr = \pi Pr^2; \quad M_2 = \int_r^R Prdr = P(R^2 - r^2), \]

where \( P \) is the rock resistance to destruction per unit length of the development radius, \( R \) is the radius of the tunnel, \( r \) is the radius that separates the circular part from the annular. Equating these two points, we find the radius of the circular part:

\[ r = R/\sqrt{2}. \]

The disadvantage of this scheme is that if in any part of the face (circular or annular) there is a site with different hardness, the moments will cease to equalize and their difference will be transferred to the rock surrounding the tunnel.

Overcoming such a drawback is possible by changing the development area. When the moment increases, for example, in the circular part, it is necessary to reduce its area, reducing the radius found and thereby increasing the ring part, and, conversely, if the moment increases in the annular part, increase this radius.

Technically, this can be done using the device described in [6], its design will be explained in Figure 3.

The equalization of moments is based on the kinematics of the differential mechanism with two sun wheels 18, 19 and satellites 20 between them, the axes 21 of which are fastened to the carrier 22.
With equal torques on the outer 2 and inner 3 rotors, with which the sun wheels and crowns 9, 11 are fastened, their rotation is carried out with equal angular speeds. In this case, the axis 21 of the satellites 20 are stationary and do not move relative to the stator 1. With increasing torque, for example, on the outer rotor 2, because of the harder rock, the angular velocity of its rotation decreases. The axis 21 of the satellites 20 are set in motion and, due to the screw connection between the carrier 22 and the plate 15, pull the plate 15 up. This movement carries along the outer leashes 14, which rotate the outer rotary washers 13, the latter, in turn, rotate the crowns 9 and reduce the annular area of development. At the same time, the inner crowns 11 are rotated through the internal leashes 17 and the inner rotary washers 16, increasing the circular development area until the cutting moments on the drill bits are balanced and the satellite axes stop moving. Similarly, the area changes if the cutting moment on the inner rotor 3 increases, only the movement of the axes 21 of the satellites 20 together with the carrier 22, plates 15, leads 14 and 17, rotary washers 13 and 16 and the crowns 9 and 11 changes direction the opposite.

On the other hand, there are many technologies that reduce the torsion moment to zero in other ways, for example, as shown in Figure 4.

Figure 3. Equalizer Design
Figure 4. Soil sampling schemes that reduce or even eliminate torque

To do this, you can divide the development area into a large but even number of rings, forcing the crowns ensuring their development to rotate in different directions (Figure 4a). At the same time, you can not resort to the complex mechanism of aligning the moments, since the moments themselves will be much smaller due to a decrease in the development area under each crown, and the likelihood that areas of different hardness will fall under the two crowns at once increases. We call this method technology with concentric crowns.

It is possible to apply an even number of independent tools simultaneously rotating in different directions (Figure 4c). The resulting tides can be cut off by swinging all the tools simultaneously around a common axis, as shown by the arrows in the figure.

Finally, when selected in any other way - for example, with a bucket (see Figure 4c) or even with erosion of the rock, the torque does not appear at all. Moreover, the presence of a shield is not excluded.

To distinguish this technology from others, we can call it the technology of direct selection of the breed.

3. Selection criteria

To compare technologies, it is necessary to determine the criteria. In this case, one should consider not only the characteristics of the machine and tool, but also the characteristics of the rock passed. This is especially important in the case of using technology with equalization of torques, since equalization is possible only when the power circuit is closed through a passable rock, this can be seen from the solution of the corresponding boundary value problem [7]. If you pass through the sand, the circuit and annular of the developed zones with respect to the tunnel will be violated and the moments will not equal each other.

As a result of this, the choice of technology should be uniquely tied to the properties of passable rocks, which can be evaluated in different ways [8-11]

At the same time, among the most widely used indicators recently [12,13], characterizing the totality of the mechanical properties of rocks, 4 are distinguished:
- RMR (Rock Mass Rating) [14] is associated with the compressive strength of the rock, fracture (taking into account the frequency of occurrence, extension and orientation of the cracks) and humidity;
- Q (Rock Mass Quality Index) is measured by fracture and internal rock stresses;
- RMBI (Rock Mass Brittleness Index) [15,16] depends on the fracturing and tensile strength of the rock both in compression and in tension;
- RMCI (Rock Mass Cuttability Index) is related to the compressive strength of the rock and its fracture.

The simplest criteria for choosing a technology related to stresses arising in the rock can be limited by three parameters: axial and radial face pressure and total or maximum torque.

In this case, it is important what general stress is created by the tool, therefore, it is necessary to use some theory of strength, for example, the theory of greatest shear stresses [17], according to which the reduced stress in a plane stress state is determined by the formula

\[ \sigma_{pr} = \sqrt{(\sigma_x - \sigma_y)^2 + 4\tau^2} \]  

(6)

where \( \sigma \) is the normal stress and \( \tau \) is the tangent. Accordingly, using formulas (1) and (2) and determining through them the stresses on the tunnel wall, we obtain

\[ \sigma_{pr} = \sqrt{\frac{F_t}{2\pi R^2\tan \psi} - \frac{F_R}{2\pi R^2\cot \psi}} + 4 \left( \frac{3M}{2\pi R^3} \right)^2 \]  

(7)

Obviously, this voltage is the main criterion for choosing a technology with a "gentle" load when tunneling. It is necessary to choose the technology that ensures the minimum value of this voltage during tunneling.

4. Data and method

To study various technologies, we use the method of comparison. We will choose four for this: 1) the technology of shield driving, 2) the technology with equalizing the moments, 3) the technology with concentric crowns and 4) the technology with direct selection of breed. At the same time, we believe that the technology of sinking with concentric crowns is organized with four crowns and allows moment imbalance of only 1/8 of the moment value during shield penetration.

The values of the parameters for calculations by the formula (7) are summarized in the table 1.

| Technology number | The radius of the tunnel, m | Axial load, kn | Torque, kn / m | Angle \( \psi \), degrees | Coefficient of friction |
|-------------------|-----------------------------|----------------|---------------|--------------------------|-----------------------|
| 1                 | 3                           | 25600          | 250           | 90                       | 0.1                   |
| 2                 | 3                           | 25600          | 0             | -                        | 0.1                   |
| 3                 | 3                           | 25600          | 40            | 45                       | 0.1                   |
| 4                 | 3                           | 12300          | 0             | 90                       | -                     |

5. Results and discussion

The calculated data allowed us to construct the following histogram, presented in Figure 5.

As you can see, the smallest stresses in the rock are created by direct selection technology, since there is no torque, and due to local selection with a small tool, the axial pressure decreases. In second place in preference is the technology with equalization of moments, however, it is based on a rather complex technical device. The largest load on the rock is provided by the shield technology of sinking due to the simultaneous presence of both axial force and torque.

6. Conclusion

Thus, a study of various tunneling technologies has shown that they can be ranked by the created stress-strain state. The stresses created in this case are influenced not only by the driving conditions in the form of axial force and torque, but also by the presence and size of the conical part of the tool, as well as torque equalizing devices.
Figure 5. Bar graph of stresses arising in the rock from sinking technology

References
[1] The code of rules SP 122.1330.2012 2012 Tunnels railway and road. Updated version of SNiP 32-04-97. (M.). 127
[2] Solonenko V G and Ryzhkin A A 2018 Metal cutting and cutting tools (M.: Infra-M) p 416
[3] Valiev A G, Vlasov S N and Samoilov V P 2003 Modern panel machines with active face loading for tunneling in difficult engineering and geological conditions (M.: TA Engineering) p 70
[4] Guidance on the design and construction of tunnels by the shield method 2009 ed V E Merkina and V P Samoilova (M.: TA Engineering) p 448
[5] The course of theoretical mechanics 2005 ed K S Kolesnikova (M.: MSTU im. N.E. Bauman) p 736
[6] Pishchukhin A M and Pishchukhina T A 2015 Improving the technology of hose-cable Drilling and Oil 11 pp 46-47
[7] Kolotvin A V and Pishchukhin A M 2015 About the formulation and solution of the boundary-value problem of drilling a well with non-rotating drill bits Bulletin of the Orenburg State University 9 pp 153-157
[8] Zhabin A B, Averin E A and Polyakov A V 2018 Rock equivalent strength index Mining 5 p 141 DOI: http://dx.doi.org/10.30686/1609-9192-2018-5-141-112-115
[9] Kýlýç A and Teymen A 2008 Determination of mechanical properties of rocks using simple methods Bulletin of Engineering Geology and the Environment V 67 2 p 237 DOI: 10.1007 / s10064-008-0128-3
[10] Khandelwal M 2013 Correlating P-wave velocity with the physico-mechanical properties of different rocks Pure and Applied Geophysics V 170 4 pp 507–514 DOI: 10.1007 / s00024-012-0556-7
[11] Morelli G L 2015 Variability of the GSI index estimated from different quan-titative methods Geotechnical and Geological Engineering V 33 4 pp 983–995 DOI: 10.1007 / s10706-015-9880-x
[12] Zhabin A B, Averin E A, Polyakov A V 2017 Integral assessment of the complexity of a mining project Coal 11 (1100) pp 60–63 DOI: 10.18796/0041-5790-2017-11-60-63
[13] Salimi A, Rostami J and Moorman C 2017 Evaluating the Suitability of Existing Rock Mass Classification Systems for TMB Performance Prediction by Using a Regression Tree Procedia Engineering V 191 pp 299-309
[14] Hamidi J K Shahriar K Rezal B and Rostami J 2010 Performance prediction of hard rock TBM using Rock Mass Rating (RMR) system Tunnelling and Underground Space Technology V25 4 pp 333-345
[15] Ebrahimabadi A, Goshtasbi K, Shahriar K and Seifabad M C 2011 A model to predict the performance of roadheaders based on the Rock Mass Brittleness Index Jornal of the Southern African Institute of Mining and Metallurgy V111 5 pp 355-364
[16] Gong Q M and Zhao J 2007 Influence of rock brittleness on TBM penetration rate in Singapore granite Tunnelling and underground space technology V22 3 pp 317-324
[17] Starovoitov E I 2010 Resistance of materials: Textbook for universities (Moscow: FIZMATLIT) p 384