Calculation of Stress-strain State of the Microtunneling Shield Housing

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Abstract. The work reviews the strength calculation of the microtunneling shield housing shell and bed plates of hydraulic cylinders of the mobile set. Based on the requirements for maximum loads on the shield, the analytical calculation of the housing shell thickness and basic design parameters of the tunneling shield bed plate was made. The bending moments and normal forces effecting on the housing were defined in analytical way. The calculation method was offered for the required solid shell of the shield housing considering the allowed values of its deformation due to the necessary construction clearance between the inner surface of the housing shell and mounted support. The numerical modelling of the stress-strain state of the tunneling shield housing was made using the finite-element method on the basis of solid model with due regard to the design peculiarities of the tunneling shield. The numerical modelling confirms the results of analytical calculation of design parameters of the tunneling shield.

1. Introduction

Currently, the majority of works on underground facilities construction in the densely populated cities and megalopolises are performed by underground method using the specialized machinery to provide for the underground facilities construction (wells, tunnels, manifold, etc.) by trenchless method that makes it possible to overcome the artificial and natural obstacles (main transport routes, railway roads, embankments, dams, rives, as well as overground and underground structures and utilities) encountered during the works, without violation of their functioning mode [1,2]. To construct the underground facilities of small diameter and relatively small length using the trenchless method, such methods as horizontally inclined drilling [3], puncturing or squeezing are used, and for medium and large diameters with large length, the tunneling shields of various modifications are used. The main advantage of the trenchless method of construction consists in possibility of construction of complex underground utilities with rather high economic efficiency in the conditions of the densely populated cities and various mining and technical conditions [4,5]. This means that the machinery designated for such works will actively develop and improve in future, as its market demand will increase and the area of application will expand [4].

The shield tunneling for construction of such facilities as tunnels, manifolds and subways has been widely used as this method has significant advantages over the alternative ones. These advantages can include the possibility of accident-free construction of facilities in complex mining and technical conditions, high work safety, high tunneling speeds, high mechanization levels and low labour capacity [6,7]. The listed advantages of the shield tunneling makes it possible to state that this method
is preferred for construction of large and medium diameter underground facilities, but is also useful for construction of small diameter facilities when the suitable equipment is available [8,9].

One of the prospective samples of the equipment for laying the utilities of 1,420 mm in diameter and over 100 m long is the tunneling shield of the microtunneling complex. This equipment provides for tunneling the mine openings of round section in stable soft rocks with the hardness of up to 3 points according to the Protodyakonov scale of hardness and dip up to 12 degrees.

2. Analytical Model

One of the basic design parameters of any tunneling shield is its outer diameter. The outer diameter of the shield provides not only for the final diameter of the development made, but also such parameters as the mass, maneuverability factor and reliability level of the machinery, in general [10,11]. The shield housing is the main load-bearing structure that perceived the loads of the rock pressure and movement efforts and on which all main mechanisms are mounted. That is why the outer diameter values are to be thoroughly calculated and substantiated.

The outer diameter of the tunneling shield is used to be determined based on the following function [12]:

\[ D_{sh} = D_{out} + t + 2\delta, \]

where \( D_{out} \) – outer diameter of finishing, mm; \( t \) – construction clearance value, mm; \( \delta \) – shield shell thickness, mm.

The outer diameter of the finishing and the construction clearance value are used from the initial data and recommendations depending on the diameter of the constructed working. The required shield shell thickness considering the regulated safety factor amounts to the system calculation, where the number of unknown supporting responses is larger than the number of independent statics equation used for the structure under consideration, i.e. to solving the statically indefinite system.

The static calculation of the shield shell is performed according to general calculation techniques of the statically indefinite system using the method of forces with transfer of unknown quantities to the elastic centre of the system and using the symmetry of the shield and external loads relative to the vertical axis. When selecting the shield load scheme, the most disadvantageous combination is used, as a rule, when the whole column of the overlying soft rocks effects the shield and there is no lateral pressure. Such load combination is possible when the shield leaves the stable rock zone and goes to the overlying unstable soft rock zone with the long stay [12].

The design system of the shield shell and its main system are shown in Fig. 1.

The symmetric equations for solving the statically indefinite framed system in accordance with Fig. 1 provided that there are no additional bandages have the form of a set of equations:

\[
\begin{cases}
    x_1\delta_{11} + \Delta_{1p} = 0, \\
    x_2\delta_{22} + \Delta_{2p} = 0,
\end{cases}
\]

where \( x_1, x_2 \) – unit undefined forces acting in the main system; \( \delta_{11}, \delta_{22} \) – unit displacements in the \( x_1 \) and \( x_2 \) directions under the action of unit forces \( x_1 \) and \( x_2 \), respectively; \( \Delta_{1p}, \Delta_{2p} \) – displacements in the \( x_1 \) and \( x_2 \) directions under the action of a given load, respectively.

Fig. 2 and 3, respectively, show the distribution diagrams of bending moments from single forces and normal forces from the acting loads on the tensile fibre in the transverse section of the tunneling shield shell.

Single shifts are determined in accordance with the ratios:

\[
\delta_{11} = \frac{2R \pi}{EI} \int_0^\varphi M_1 d\varphi,
\]

where \( R \) – radius of curvature; \( \varphi \) – angle of displacement; \( M_1 \) – bending moment acting at the point of action of the load; \( E \) – Young’s modulus; \( I \) – second moment of area about the neutral axis.
Figure 1. Transverse section of the tunnelling shield shell: $a$ – design scheme; $b$ – main system of forces.

Figure 2. Distribution diagrams of bending moments from single forces.

Figure 3. Distribution diagrams of normal forces from single forces.

\[ \delta_{22} = \frac{2R}{EI} \int_0^{\pi/2} R \cos(\phi) d\phi, \]

\[ \Delta_{1p} = 2R \left[ \int_0^{\pi/2} \frac{qR^2}{2} \sin^2(\phi) d\phi + \int_0^\pi \frac{qR^2}{2} (\sin(\phi) - 0.5) d\phi + \int_\frac{\pi}{2}^{\pi} \frac{qR^2}{2} (\sin(\phi) - 0.5) + \frac{qR}{2a} (a - R \sin(\phi))^2 \right] d\phi. \]

\[ \Delta_{2p} = 2R \left[ \int_0^{\pi/2} R \cos(\phi) \frac{qR^2}{2} \sin^2(\phi) d\phi + \int_0^\pi R \cos(\phi) qR^2 (\sin(\phi) - 0.5) d\phi + \int_\frac{\pi}{2}^{\pi} qR^2 (\sin(\phi) - 0.5) + \frac{qR}{2a} (a - R \sin(\phi))^2 \right] d\phi. \]
where \( R \) – the radius of the tunneling shield housing shell; \( E \) – elasticity module; \( I \) – moment of inertia; \( M_1 \) – bending moment on the component \( x_1 \), \( q \) – vertical load intensity per a meter of horizontal diameter of the tunneling shield housing.

The vertical load intensity per a meter of horizontal diameter of the tunneling shield housing \( q \) depends on the design shield depth, average volumetric mass of the overlaying rocks, design length of the shield housing and shall be determined according to the formulae:

\[
q = H\gamma L_{des} g,
\]

(7)

where \( H \) – shield depth; \( \gamma \) – average volumetric mass of the overlaying rocks; \( L_{des} \) – design length of the tunneling shield housing.

Bending moments effecting the tunneling shield housing are determined in accordance with the functions:

- from 0 to \( \pi/2 \):

\[
M = x_1 + x_2 R\cos(\varphi) + \frac{qR^2}{2} \sin^2(\varphi),
\]

(8)

- from \( \pi/2 \) to \( \beta_1 \):

\[
M = x_1 + x_2 R\cos(\varphi) + qR^2(\sin(\varphi) - 0.5),
\]

(9)

- from \( \beta_1 \) to \( \pi \):

\[
M = x_1 + x_2 R\cos(\varphi) + qR^2(\sin(\varphi) - 0.5) + \frac{qR}{2a}(a - R\sin(\varphi))^2
\]

(10)

To determine the bending moments and normal forces effecting the housing and the shell of the tunneling shield, respectively, a section with the most acting stress is selected and the future calculation is performed for this section.

To determine the main design parameters of the support ring of the tunneling shield designated for supporting and securing the shield jacks, as well as for the supply effort transfer from the shield jacks to the cutter-base plate, it is necessary to make assumption that a separate ring segment restricted by the strengthening ribs (kneepieces) acts to clear bending and represents a bar on two fixed supports. The design schemes of the support ring and its segment are given in Fig. 4 and 5, respectively.

\[\text{Figure 4. Design scheme of the support ring.}\]

\[\text{Figure 5. Support ring segment with dangerous section.}\]

The dangerous section in the support ring segment is A-A section. To determine the acting stresses in the A-A support ring segment section, the following function should be used:

\[
\sigma = \frac{M_{bend}}{W},
\]

(11)

where \( M_{bend} \) – bending moment in the A-A section; \( W \) – A-A section modulus.

The section modulus \( W \) is determined according to the formulae:
\[
W = \frac{\delta (h^3 - d_d^3)}{6h},
\]

where \( \delta \) – support ring thickness; \( h \) – support ring segment width; \( d_d \) – diameter of support ring segment opening for the jack.

This means that the support ring thickness can be defined from the following:

\[
\delta = \frac{6h^2 F_d n}{2\sigma_T (h^3 - d_d^3)},
\]

where \( F_d \) – point loading acting in the dangerous section; \( n \) – specified safety factor of the support ring; \( \sigma_T \) – yield point of the material of support ring production.

3. Numerical Modelling

The offered technique does consider the tunneling shield as a complex object, with some inner design components directly effect the stress-strain state of the housing shell. To assess the stress-strain state of the shield housing shell, the numerical calculation was performed using the finite-element method in the numerical modelling environment SALOME-MECA v2018 [13,14].

The geometrical model of the microtunneling shield housing (Fig. 6) was created using the Geometry module tools of the numerical modelling platform SALOME-MECA. The housing model contains the internal power design elements: two support rings of thrust cylinders, cutter-base plate with the bearing housing and main drive shaft of the control, ratchet gear levellers of the main drive shaft, support plates of the brackets of the main drive shaft hydraulic cylinders.

![Figure 6. Longitudinal section of the geometrical model of the shield housing model (1 - main drive shaft, 2 - bearing housing of the main drive shaft, 3 - blade-bed plate, 4 - main drive link, 5 - bracket support of the main shaft hydraulic cylinder, 6 - support rings, 7 - housing shell).](image)

The finite-element mesh is created using the Mesh module tools of the numerical modelling platform SALOME-MECA.

The basic characteristics of the finite-element length are limited by the value range of 5-10 mm. The degree of the finite-element optimization by quality is set as "VeryFine". The automatic conversion of the tetrahedral mesh into the quadrahedral one and adjustment of the matching units were performed. The finite-element mesh contains 166090 nodes and 8451766 elements, 8012006 of which are three-dimensional.

The three-dimensional finite-element mesh has the separated surfaces of the forces applied that effect the design elements of the tunneling shield housing in the form of two-dimensional finite-element groups. The forces applied to such surfaces are uniformly distributed. The modelling of the forces applied was performed by using the operator FORCE_FACE, function AFFE_CHAR_MECA, "AsterStudy" module of the numerical modelling platform SALOME-MECA. The ground friction...
forces (459 kN) and vertical rock pressure forces (based on the rock pressure value of 0.85 MPa) are applied to the external surfaces (except for the end surfaces) of the shield housing shell. The force of resistance to intrusion of the shield housing edge into the rock was applied to the front end surface of the shield housing shell (1,340 kN). The basic surfaces relative to which the calculation of the stress-strain state of the shield housing is performed are the joint faces of the support rings of thrust cylinder. The linear static model "LinearStaticAnalysis" (function MECA_STATIQUE), "AsterStudy" module, was used for calculation of the stress-strain state. The calculation results of the stress-strain state of the microtunneling shield housing are given in the form of charts of equivalent stresses and strains in the shield housing. Post-processing and visualization of the calculation results of equivalent stresses and strains were performed using the integrated software tools of the "ParaVis" module [15-17] of the numerical modelling platform SALOME-MECA.

The calculation results established that the most strains of the microtunneling shield housing are observed on termination of the tail part. The strain value does not exceed 15 mm (Fig. 7) that is 4.7 times higher than the maximum constriction clearance (not more than 70 mm). The peak stress values in the shield housing do not exceed 530 MPa (Fig. 8) that makes it possible to use steel 14CrMn2SiVCu.

![Figure 7. Chart of the shield housing strain.](image1)

![Figure 8. Chart of stress distribution in the tunneling shield housing.](image2)

Considering the obtained results, the reasonability of reduction in the tunneling shield shell thickness was assessed.

### 4. Conclusion
The given technique for determination of such design parameters of the tunneling shield as the housing shell thickness and support ring thickness provides for calculation of the specified design parameters considering the shield mass reduction provided that the regulated safety factor is preserved that will make it possible to create its balanced structure from the strength point of view in future.

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