Strength calculation method of reinforced concrete structures of Tashkent underground tunnels with different stages of stress condition

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Abstract. Modern requirements of engineering practice in tunnel construction are related to the problems of strength and the identification of reserves of bearing capacity of tunnel lining. The achieved success in creating rational reinforced concrete structures of tunnel linings is largely determined by the results obtained in the field of mathematical and mechanical modeling of deformation processes. Reinforced concrete large-sized building structures constitute the main structural elements of the Tashkent underground tunnels in Uzbekistan, as reinforced concrete under proper conditions gives a significant technical and economic effect, reducing the time and cost of construction. Experiments on the bending of reinforced concrete beams with a gradually increasing load indicate various stages of the stress condition. To achieve the most economical consumption of materials, it is proposed to calculate structures for the forces that act under breaking load. This paper presents a method for calculating the lining of reinforced concrete tunnels of the Tashkent underground based on the more accurate assessment of the fundamental properties of reinforced concrete that determine its behavior under external load.

1. Introduction
In our country, special attention is paid to the development of road construction, to the implementation of measures to improve and build strength systems for underground facilities under various external influences. Large-sized reinforced concrete building structures form the main structural elements of the tunnels of the Tashkent underground (metro), as reinforced concrete under proper conditions (availability of the reinforced concrete plant, favorable conditions for transportation and installation of prefabricated elements) provides a significant technical and economic effect, reducing the time and cost of construction.

However, a recently conducted analysis reveals serious defects and damages in the structures (figure 1), and this puts forward a number of requirements in the design of transport tunnels, in particular, more and more necessary up-to-date calculation methods compared to existing [1].
Figure 1. Defects on the tunnel linings of Tashkent underground.

Experiments on the bending of reinforced concrete beams with a gradually increasing load indicate various stages of the stress condition (figure 2). At the beginning of loading, the stresses are almost proportional to the elongations, but with the increasing load, the stress diagram acquires a curvilinear outline. The further increase in the load leads to an elongation of the extreme stretched fibers to such an extent that the concrete starts to break. Next comes the stage of destruction, where the stress in the reinforcement reaches the yield strength, or the compressed concrete zone is destroyed at stresses equal to the compressive strength of concrete. This stage is the basis for the calculation of the first limit state in the building specifications. It should be noted that in this case, the position of the neutral axis in different stages moves to the compressed face of the section [2].

Figure 2. Stages of the stress condition in section of the reinforced concrete element.

The calculation method on limiting states given in specifications for reinforced concrete structures refers only to the determination of the strength of sections and internal forces, and is usually done as for a homogeneous elastic body. In fact, at the beginning of the destruction stage, the distribution of forces in statically indeterminate reinforced concrete structures differs significantly from that observed in the elastic stage. In this regard, the method and algorithm for calculating the bending moment and normal forces in reinforced concrete elements were considered, taking into account all stages of the stress state.

2. Formulation of the problem
A mathematical model is proposed for calculating deformation in tunnels, taking into account the bearing reaction of soil. Here repulse pressures occur at the point when the displacements of lining take place in the radial direction at the contact of soil. At contact points where there are no relative displacements (non-reaction areas), the specified soil pressures in the indicated directions remain unchanged [3]. To simulate the elements of tunnel structures in a plane problem, a beam model with
corresponding boundary conditions is used. The elements are connected in nodes, where each element has six degrees of freedom (figure 3).

The following matrix equations represent a mathematical model for calculating the stress of tunnel lining interacting with the soil:

\[
\begin{align*}
\Delta S &= \tilde{P} - K \cdot (\tilde{Z} - \tilde{Z}_g) \\
A^T \tilde{Z} &= \tilde{\lambda} \\
D \Delta S &= \Delta \lambda
\end{align*}
\]

Here \( A \) is global equilibrium equation matrix, \( \Delta S \) is internal force vector in beams, \( \tilde{P} \) is vector of nodal external forces, \( K \) is matrix of interaction coefficients (bearing reactions) of the beam system with soil, \( \tilde{Z} \) is nodal displacement vector, \( \tilde{Z}_g \) is nodal displacement vector of soil, \( D \) is quasi-diagonal matrix of Hooke's law, \( \Delta \lambda \) is strain vector of elements.

After solving the problem, we determine the displacements and angular deflections in each node of the structure. Knowing the displacements and angular deflections, we can determine the bending moment and normal force in each structural element, which are then used to calculate the correctness of the selected section sizes.

![Figure 3. Partitioning scheme for elements.](image)

In the mathematical model, when considering a nonlinear calculation, we assume that the material of the structure follows a certain diagram [4]. For a plane task, dividing the load (in portions) by sequentially setting the parameter \( \lambda_n \), we obtain the following relationship taking into account the increment of displacements.

\[
\Delta \tilde{Z}_n = (K_T(\tilde{Z}) + \tilde{K})^{-1} \Delta \lambda_n (\tilde{P} + \tilde{K} \tilde{Z}_f), \quad \tilde{Z}_n = \sum_{i=1}^{n} \Delta \tilde{Z}_n, \quad \Delta \lambda_n = \lambda_{n+1} - \lambda_n
\]

The problem-solving procedure involves the linear problem solution at the first load step and after determining the displacement vector of a discrete system, at each subsequent step the corresponding nonlinear system matrices are corrected. Here \( K_T(\tilde{Z}) \) is the tangential stiffness matrix, which takes into consideration the forces in the elements of the system during the transition from step to step.
3. Algorithmization of calculation method
The algorithm for calculating of reinforced concrete tunnel structures under load is implemented. Structural analysis is performed in the nonlinear formulation. It uses a step-by-step method where the load is applied to the structure as portions, and on each portion of load increment, a solution is searched, which is then summed with the previous solutions. On the diagrams of deformation of materials are the determined stress and tangent modulus of elasticity (figure 4). The resulting stiffness is introduced into the calculation at the next step of increment of the load until the design load is achieved.

![Figure 4. Determination of modulus of elasticity.](image)

![Figure 5. Scheme of dividing the cross-section to layers.](image)

Method for determining the geometrical and physical characteristics of the cross-section for each load increment is based on the following scheme: the structure is described by a combination of calculated cross sections, each of which is considered consisting of \( n \) layers (figure 5). All \( n \) layers in one section have the same height \( h \), then total section height is written as:

\[
H = \sum_{i=1}^{n} h_i
\]

In the design section, each \( i \) layer is conventionally regarded as rectangular, with a width.

Deformation properties of materials are characterized by tested diagrams. Each diagram is given in the form of two tables: stresses values and corresponding values of relative strains. In the process of calculation, it is accepted that sections remain plane. Before loading, all layers of the design section of a beam have the initial modulus of elasticity. After loading starts, between each load increment for each layer of section modulus of elasticity is determined based on the value of the strain in this layer. Therefore, section bending stiffness \( EI \) and compressive stiffness \( EF \) are taken as the sum of layers that,

\[
EI = \sum_{i=1}^{n} E_i(\varepsilon)I_i \quad EF = \sum_{i=1}^{n} E_i(\varepsilon)F_i
\]

where \( E \) is the sectional modulus of elasticity, \( I \) is the sectional moment of inertia; \( n \) is the number of layers, \( E_i, I_i, F_i \) are the modulus of elasticity, moment of inertia and cross-sectional area of the \( i \) layer,
respectively. Moments of inertia of cross-sectional layers are determined relative to the horizontal axis of coordinates by the formula,

\[ y_c = \frac{\sum_{i=1}^{n} \Delta F_i E_i y_i}{\sum_{i=1}^{n} \Delta F_i E_i} = \frac{\Delta F_1 E_1 y_1 + \Delta F_2 E_2 y_2 + \ldots + \Delta F_n E_n y_n}{\Delta F_1 E_1 + \Delta F_2 E_2 + \ldots + \Delta F_n E_n} \]  

(5)

\[ \Delta F_i = h_i b_i \]

The moment of inertia of the rectangle \( i \) (layer) on the axis is,

\[ I_{i,c} = \frac{b_i h_i^3}{12} + (y_c - y_i)^2 b_i h_i \]  

(6)

Knowing the deformation of the bending moment, it is possible to determine the stress which will be equal to \( \sigma_i = E_i \varepsilon_i \) [4].

4. Numerical results and discussions

Let us consider the solution of deformation of reinforced concrete tunnel lining as arch structure. The span of tunnel arch is 20,6270 m, rise of arch is 7,5703 m (figure 6). Arch covered with backfill soil height 0,75 m with volume weight is \( \gamma = 19 \text{ kN/m}^3 \), on 0,25 m there is asphalt pavement, where volume weight is \( \gamma = 24 \text{ kN/m}^3 \). Arch is made of concrete with strength class B35. Design strength of concrete is accepted according to the regulation [5]: \( R_b = 17500 \text{ kN/m}^2 \) is axial compression; \( R_{bt} = 1150 \text{ kN/m}^2 \) is axial tension; \( E_b = 28 \cdot 10^6 \text{ kN/m}^2 \) is modulus of elasticity of concrete; \( \gamma_b = 25 \text{ kN/m}^3 \) is the volume weight of concrete; \( \varepsilon_{b1} = 0,0003 \) is strain of lower branch from diagram of concrete compression; \( \varepsilon_{b0} = 0,00092 \) is strain of upper branch from diagram of concrete compression;

Cross-section of the tunnel arch and vaulted elements which are reinforced with longitudinal reinforcement in diameter 20 mm and 25 mm steel has class A-III, and thus, the following is accepted (figure 7): \( R_{pn} = 390000 \text{ kN/m}^2 \) is regulatory tensile resistance of reinforcement; \( E_p = 2 \cdot 10^8 \text{ kN/m}^2 \) is the modulus of elasticity of reinforcement. The bearing reaction value of surrounding soil is \( k = 2 \cdot 10^8 \text{ kN/m}^2 \).

Figure 6. Loaded scheme of tunnel arch span, (m).
The following parameters are entered in this case, \( F=0.3629469 \, \text{m}^2 \), \( J=0.009763039 \, \text{m}^4 \) for the computation. During numerical researches, the normal stresses and strains in sections of a reinforced concrete arched structure were calculated. Results of calculations are presented in the form of diagrams (figure 8 and figure 9). These researches have allowed the determination of the mechanism of work of reinforced concrete arched structure in a body of soil at the admission on its modern transport loadings. In the first phase, internal forces are estimated taking into account the dead weight of the arch, the weight of the overlapping pavement and surrounding soil. Then, the following option is considered, where the temporary car load is moving in two variants: in the middle of a half-span and span of the arch.

**Figure 7.** Scheme of cross section of vaulted element, (mm): a) existing section, b) reduced section.

**Figure 8.** Distribution of deflections (m) and moments (kNm) obtained from elastoplastic calculation: a) deflection diagram, b) moment diagram.

Elastoplastic calculation showed that the application of nonlinear deformation diagrams of reinforcement and concrete changes the stress distribution in the cross sections of the arch. Analyses show that the most loaded is considered the second option, i.e. when the car load is in the middle of the tunnel. In this case, the arch structure accepts the maximum internal forces in its sections.
Reinforcement in the tension zone and concrete in the compression zone are working with the stress safety factor.

![Figure 9](image_url) Distribution of maximum layer stresses (kN/m²) and strains on height of cross-section of arch element.

5. Conclusions

In the Republic of Uzbekistan, special attention is paid to the development of road construction, to the implementation of measures to improve and build strength systems for underground facilities under various external influences. Large-sized reinforced concrete building structures form the main structural elements of the tunnels of the Tashkent underground (metro), as reinforced concrete under proper conditions (availability of the reinforced concrete plant, favorable conditions for transportation and installation of prefabricated elements) provides a significant technical and economic effect, reducing the time and cost of construction.

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The solution of deformation of reinforced concrete tunnel lining is considered as an arch structure. During numerical researches the normal stresses and strains in sections of a reinforced concrete arched structure were obtained. Results of calculations are presented in the form of diagrams. These researches have allowed the determination of the mechanism of work of reinforced concrete arched structure in a body of soil at the admission on its modern transport loadings.

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