Modelling of the stress-strain state of a transport tunnel under load as a measure to reduce operational risks to transportation facilities

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Abstract. In many countries economic policy has been paying increasing attention to the modernization and development of transport infrastructure as a measure of macroeconomic stimulation. Tunnels as an important component of transport infrastructure save a lot of logistical costs. It stimulates increasing freight and passenger traffic as well as the risks of the consequences of unforeseen overloads. The objective of the paper is to suggest the way to reduce operational risks of unforeseen moving load by modeling of the stress-strain state of a transport tunnel under growing load for different conditions and geophysical parameters.

The article presents the results of a study of the stress-strain state (SSS) of a transport tunnel exposed to a mobile surface load. Numerical experiments carried out in the ANSYS software package made it possible to obtain diagrams showing the distribution of equivalent stresses (von Mises stresses) according to the finite element model of the tunnel. The research results give grounds to assert that from external factors the stress state of the tunnel is mainly influenced by the distance to the moving load. The results obtained make it possible to predict in advance the parameters of the stress-strain state in the near-contour area of the tunnel and use the results in the subsequent design of underground facilities, as well as to increase their reliability and operational safety.

This investigation gives an opportunity not only to reduce operational risks at the design stage, but to choose an optimal balance between investigation costs and benefits of safety usage period prolongation.

1. Introduction

Over the past decade, economic policy has been paying increasing attention to the development and modernization of transport infrastructure as a measure of neo-Keynesian model of government stimulation of the economy not only in developed but also in rapidly developing countries, as well as in countries of the former Soviet Union.

The change of priorities in economic policy is connected not only with the crisis of monetary regulation of the world economy and the need to strengthen budget financing of infrastructure projects
as an important measure to support the economy and promote full employment in the post-crisis period. Modernization and construction of transport infrastructure on a new technological basis also requires the transition of the world economy to the technologies of the fourth industrial revolution [1].

However, in addition to macroeconomic and technological problems, for the successful and long-term functioning of the transport infrastructure with increasing loads, it is necessary to address the issues of reducing operational risks, the occurrence of which can neutralize the macroeconomic and logistic effect. This issue should be resolved already at the design stage.

Tunnels of varying depth are an important component of the transport infrastructure. Their use can significantly reduce distances, which seriously reduce logistical costs, increasing freight and passenger traffic, and, consequently, the risks of the consequences of unforeseen loads.

Thus, despite the high cost, complexity and labor intensity of the work, the tendency to increase the volume of tunnels and underground facilities is common to all developed countries of the world. Tunnels are one of the main structures that make up transport systems. When designing such objects, it is necessary to take into account the deformation characteristics of the enclosing rock mass, the depth and cross-sectional dimensions of the tunnels, as well as various types of loads and effects that affect the stress state of underground structures. Violation of the integrity of the soil mass changes the stress-strain state of the mass, including along the contour of the tunnel. This leads to the appearance of tensile stresses in some places, and compression stresses in others [2]. Loads and impacts on tunnels are classified as permanent and temporary. Rock pressure refers to permanent loads and influences on tunnels. Temporary loads include moving loads from vehicles travelling both inside and outside the tunnel. For shallow tunnels such loads are of particular importance. Researches [3] have established that the contour of the tunnel is affected by vehicles passing along parallel paths. If the resulting stresses exceed the calculated tensile and compressive resistances of the soil, then, accordingly, the roof may collapse and the side walls of the tunnel walls [4]. In other words, this will lead to the loss of the bearing capacity of the tunnel structures or its unsuitability for normal operation.

In the works of a number of authors, methods for calculating parallel interacting shallow tunnels have been proposed, which make it possible to take into account the effect of acting dynamic loads. N.N. Fotieva, A.S. Sammal, S.V. Antsiferov [5] developed methods for calculating lining of parallel, mutually influencing shallow circular tunnels on the action of the own weight of rocks, groundwater pressure, internal pressure, weight of objects, dynamic loads and on the seismic effects of earthquakes.

Methods for calculating the linings of shallow tunnels experiencing various kinds of loads and impacts are proposed in the work [6]. The methods are based on solving the corresponding plane problems of the theory of elasticity for an isotropic medium that simulates a rock mass, weakened by an arbitrary number of circular holes of different radii. The lining and the environment are deformed as a single system, the loads and impacts are modeled by the initial stress field in the rock mass caused by the action of the gravity of the rocks, the hydrostatic pressure of groundwater, and the effect of seismic waves during earthquakes. In this case, the inner contours of the lining are free from external forces. All the methods described above are based on solutions of the corresponding problems of the theory of elasticity.

To create a mathematical model of the functioning of the "highway – mountain range - tunnel" system, a systematic approach based on formalized methods is necessary. Applying them sequentially make it possible to identify the relationships of elementary structural units (subsystems) of the modeling object; determine the structure and relationship between the elements; evaluate their properties and parameters; identify the relationship between the parameters and the resulting indicators. Based on this approach, mathematical models allow analysis and structural synthesis of a complex system using formalized methods.
2. Materials and research methods

2.1. Problem statement
There is a large number of works in which the impact on the stress state of the tunnel is investigated by a vehicle moving along it or in parallel shallow tunnels, effective analytical and numerical methods of calculation have been developed [7-11]. At the same time, the impact on tunnels of moving loads from ground transport remains unexplored, although the world practice of operating tunnels indicates numerous damages and destruction these structures are exposed as a result of their impact. The aim of the work is to establish the influence on the shallow transport tunnel of the influences from the side of the passing ground vehicle (car). The task of the research was to determine the stress-strain state in the area of the tunnel, caused by the impact of a ground vehicle when its speed changes, as well as the distance between the tunnel and the load.

2.2. Problems solving algorithms
A complex system of transport structures is considered, consisting of a shallow tunnel, near which a motorway passes. The design diagram of this design is shown in Figure 1.

![Figure 1. Calculation model of the studied area of the mass.](image)

It should be noted that near the tunnel and in places of geometric heterogeneities of the elastic mass there will be concentrations of mechanical stresses. In the described formulation of the problem, the following conditions are taken into account:
1. A geostatic force is constantly acting on the entire system of "mass with a mountain slope - road and railway track in a tunnel".
2. A road located on a mountain slope is a subject of loads from the side of objects passing along it.
3. The base of the tunnel is subjected to loads from the objects passing through it.

Due to the limited capabilities of analytical methods, when solving problems related to the stability of inhomogeneous media with different shapes and boundaries, modeling is applied using effective numerical methods, among which the finite element method (FEM) is the most widespread. Currently, this method is a universal numerical method for calculating the static and dynamic strength of any objects. The loads considered above can be specified in the form of mutually independent vectors:

$$\{K\} \cdot \{U\} = \{P\}_{\text{geost}} + \{P\}_{\text{road}} + \{P\}_{\text{tunnel}},$$  

where $\{P\}_{\text{geost}}$ are forces from the natural weight of the mountain range; $\{P\}_{\text{road}}$ are forces arising from the impact of various objects on the road; $\{P\}_{\text{tunnel}}$ are forces arising from the impact of objects on the base of the tunnel.

After solving the system of equations (1), the components of the displacement vector become known. The strain and stress components in each finite element are sequentially calculated using the following known relations of the finite element method:
\{ \varepsilon \} = [B][U], \quad (2)

\{ \sigma \} = [D][\dot{\varepsilon}], \quad (3)

where \{ \varepsilon \} = \{ \varepsilon_x, \varepsilon_y, \gamma_{xz} \} are the components of the deformation, \[B\] is the matrix of basis functions, \{U\} = \{u, v\} is the vector components of the displacement, \{ \sigma \} = \{ \sigma_x, \sigma_y, \tau_{xz} \} is the vector components of the stresses, \[D\] is the matrix of elastic characteristics.

Using these stress components, the maximum and minimum principal stresses in each element \( \sigma_{\text{max}, \text{min}} \) are calculated as well as the directions of the main areas \( \alpha \) :

\[
\sigma_{\text{max}, \text{min}} = \frac{1}{2} (\sigma_x + \sigma_z) \pm \sqrt{\left(\frac{\sigma_x - \sigma_z}{2}\right)^2 + \tau_{xz}^2},
\]

\[
\tau_{\text{max}, \text{min}} = \pm \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2},
\]

\[
tg 2\alpha = \frac{2\tau_{xz}}{\sigma_x - \sigma_z}.
\]

To construct diagrams of elastic stresses arising along the contour of the tunnel, due to the effect of combinations of loads, it is necessary to determine the components of tangential stresses for any section of the contour of the tunnel. For this purpose, the known relations of the elasticity theory are used [7]. Using the stress components \( \{ \sigma \} = \{ \sigma_x, \sigma_z, \tau_{xz} \} \), written in the Cartesian coordinate system, the stress components in the polar coordinate system are calculated as:

\[
\sigma_r = \sigma_x \cos^2 \theta + \sigma_z \sin^2 \theta + 2\tau_{xz} \sin \theta \cos \theta,
\]

\[
\sigma_\theta = \sigma_x \sin^2 \theta + \sigma_z \cos^2 \theta - 2\tau_{xz} \sin \theta \cos \theta,
\]

\[
\tau_{r\theta} = (\sigma_x - \sigma_z) \sin \theta \cos \theta + \tau_{xz} (\cos^2 \theta - \sin^2 \theta).
\]

In the expression (6) are polar angles, i.e. angles between the normals to the contour and the axes of the Cartesian coordinate system.

In this work the stress state analysis was carried out by the finite element method using the ANSYS software package. ANSYS is a universal software system based on the finite element method, which allows not only to model high-quality systems of various physical nature, but also to study the response of these systems to external influences in the form of distribution of stresses, temperatures, velocities, etc.

When assigning the load value, the local load distributed over the wheel projections was averaged and applied to the entire area of the car. The dimensions of the mass are selected from the damping conditions of its stress-strain state (SSS) and are assumed to be equal to three diameters of tunnels in the corresponding directions [13]. The lower border of the mass is fixed from vertical movements, and the side borders are fixed from horizontal ones along the normal lines to the surfaces. Fine-grained sand with the following characteristics is used as a mass: elastic modulus \( E = 4 \times 10^7 \) Pa, Poisson's ratio \( \mu = 0.3 \), density \( \rho = 2000 \) kg / m³ and internal friction angle equal to 38 degrees. The process of precipitation of a mass is modeled by assigning elastic-plastic properties in the form of the Drucker-Prager law [7]. According to the Drucker-Prager strength criterion, it is assumed that the yield surface does not change with the growth of plastic deformations, i.e. there is no hardening effect, and the material is ideally elastic plastic. Modeling of the surrounding soil and tunnel is performed using SOLID45 finite elements [1].

The calculations used free splitting of the finite element grid with condensation in the vicinity of the tunnel.
The computational procedure is represented as a sequence of steps with varying values of the distance (6, 12, and 18 meters) between the highway and the tunnel. The roadway was loaded with a moving load corresponding to the speed of the passing vehicle (40, 60 and 80 km/h). The load was applied in three steps with linear variation of the force.

3. Research results
The conclusion about the reliability of structures should be made on the basis of comparing the ultimate stresses that arise at the most dangerous points with the maximum permissible limits for a given material. The operation reliability turns out to be the higher the further from the limiting state the level of actual stresses inside the mass material. The use of ANSYS programs for calculating the stress state of a tunnel makes it possible to obtain output results in the form of a stress field in various versions, of which the Mises equivalent stresses provide the most complete information.

Von Mises stress fields (equivalent stresses according to the theory of strength of the energy of deformation) in the considered mass, depending on the distance between the tunnel and the mobile load moving at a speed of 60 km/h, are shown in Figures 2-4.

![Von Mises stress fields at a distance from the tunnel to the carriageway 6 m.](image1)

![Von Mises stress fields at a distance from the tunnel to the carriageway 12 m.](image2)

![Von Mises stress fields at a distance from the tunnel to the carriageway 18 m.](image3)

It can be seen from them that the greatest deformations occur on the surface of the carriageway under a moving vehicle, somewhat decreasing as the load moves away from the tunnel. The magnitude
of these deformations is insignificant. From Figure 2 it follows that in close proximity the load has a significant effect on the stress state of the rock mass in the vicinity of the tunnel.

At the load application site, the compressive stresses take maximum values and extend deep into a large area, completely covering the tunnel contour. In this case, the greatest stresses occur on the side surface of the tunnel from the side of the acting load. The bottom of the tunnel practically does not experience additional loads, minor stresses occur on its roof and in the lower corners. With distance, the influence of the moving load on the stress state of the tunnel decreases. In this case, the stress field shifts after the load and at a distance of 12 meters, stress changes occur only in the lower corner of the tunnel from the side of the active load (Figure 3). Further increase in the distance to the load practically does not affect the stress state of the tunnel (Figure 4).

To account for the impact of vehicle speed on the stress state of the tunnel, options with different speeds were considered. Figure 2 shows von Mises stress fields at a vehicle speed of 60 km / h. The stress distributions at speeds of 40 km / h (Figure 5) and 80 km / h (Figure 6) turned out to be identical to those considered. It can be argued that in the specified range, the vehicle speed does not significantly affect the nature of the stress distribution.

4. Conclusion

The research results showed that there is a certain relationship between the external moving load and the stress state of the tunnel. The main factor affecting the change in the stress structure of a system is the distance to the moving load. In this case, the speed of the vehicle does not significantly affect the stress state of the tunnel. Consequently, when designing underground structures, it is necessary to take a more detailed approach to the choice of its location, the presence of highways nearby as well as the issue of ensuring the bearing capacity of structural elements of their lining.

The use of the research data helps to reduce operational and economic risks of unpredictable costs and accidents resulting from unexpectedly growing loads and underfunding of investigation.

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