Sergey B. Kosytsyn - Vladimir Y. Akulich*

STRESS-STRAIN STATE OF A CYLINDRICAL SHELL OF A TUNNEL USING CONSTRUCTION STAGE ANALYSIS

The work is aimed at research of the stress-strain state of a cylindrical shell of a tunnel using the non-linear static analysis and construction stage analysis. Research is carried out on the example of determining the stress-strain state of the tubing (shells) of the main line tunnel, constructed using a tunnel powered complex (slurry shield). Based on obtained results, a comparative analysis of the computational models with the corresponding conclusions is presented.

Keywords: *construction stages, soil massif, shell, slurry shield, finite elements*

1. Introduction

The technology of construction of artificial constructions, as a rule, assumes construction of objects in several stages: installation of the bridge span, installation of tubing of the main line tunnels, etc. However, now at the stage of design of such artificial constructions, computational models usually do not consider stage-by-stage construction of an object, standard and methodical documentation also does not tell anything about it. At the same time, it is worth noting that the introduction of computational models capable of changing in time is a necessary step for development of design and building of artificial constructions both on the domestic and the world scales. This is due to the fact that the stress-strain state of the computational model can significantly change when taking into account its changes in time. In this regard the comparative analysis of computational models, with and without taking into account their changes in time, is of a particular interest.

The authors of the article are aimed at the task of carrying out the comparative analysis of the final stress-strain state of the cylindrical shell of the main line tunnel, constructed using a tunnel powered complex (slurry shield). Besides the two computational models, which take or do not take into account changes in time, the third case participated in comparative analysis. It takes into account a construction gap between the tunnel shell and the soil environment, whose emergence is caused by use of the slurry shield. In addition, it was necessary to give an assessment for need of creation of a computational model taking into account change in time, when determining the stress-strain state of the complex objects constructed in several stages.

2. General provisions of calculation models

The calculation of the stress-strain state of a tunnel shell was performed by a finite element method in the ANSYS Mechanical software package. This is a complex multi-purpose software package for numerical simulation of physical processes and phenomena in the field strength, fluid dynamics, thermal physics, electromagnetism and acoustics.

The spatial calculation model (Figure 1) consisted of the isotropic uniform massif modeling the soil environment, represented by the three-dimensional quadratic isoparametric elements Hex20, each consisting of twenty nodes, and the cylindrical shell consisting of fifteen separate rings simulating the main line tunnel (Figure 2) placed in the center of the massif. The cylindrical shell is approximated by the two-dimensional flat four-node Quad4 elements. The local coordinate systems of the shell elements were co-directed, for a correct display of results.

Geometrical characteristics of the tunnel shell:

- external diameter 5800 [mm];
- internal diameter 5300 [mm];
- average length of a face ring along the tunnel 1400 [mm];
- block thickness 250 [mm].

The shell is presented by a model of linear-elastic material with the following characteristics of reinforced concrete: density - 2300 kg/m^3, elastic modulus E - 30000 MPa, Poisson's ratio μ - 0.18 (the tunnel is designed in monolithic reinforced concrete from B45 concrete and bars of A240, A400).

It is worth noting that the shell was modeled taking into account eccentricity between the geometrical shape of the cross section necessary for creation of constructive positioning of elements and the average line of a shell, along which the loading is placed and results are calculated [1].

The soil massif was set by dimensions of 65 m × 65 m × 21 m on Mohr-Coulomb model with the following characteristics of clay: density - 2000 kg/m^3, deformation modulus E_{def} - 30.0 MPa, Poisson's ratio μ - 0.30, friction angle ϕ - 20.0°, cohesion C_u - 50.0 kPa.

The problem was solved in geometrically, physically (nonlinearity of material behavior) and constructively (change of the status of contact) nonlinear statement.

The geometry of some types of designs, such as shells, having small thickness in comparison to other dimensions, can significantly change during the loading process. The stiffness of such designs changes in the course of deformation, as well [2].

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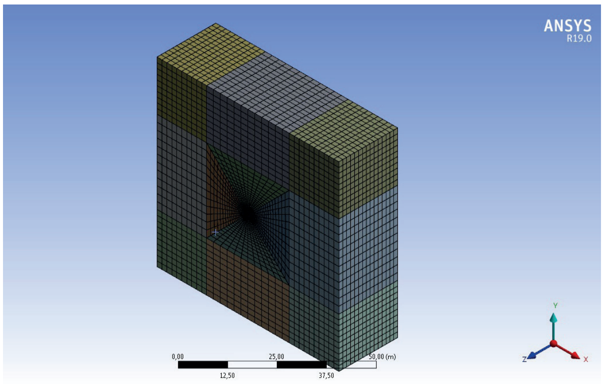

***Figure 1** Spatial calculation model in ANSYS Mechanical*

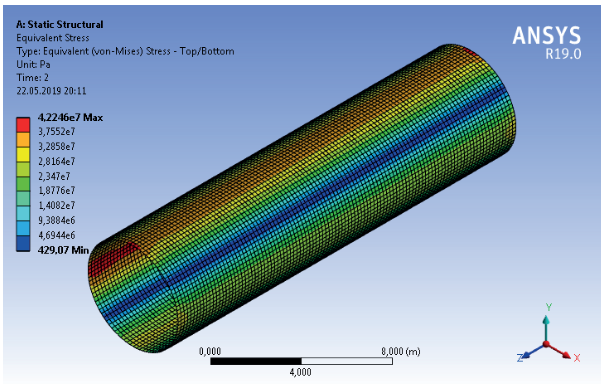

***Figure 3** Computational model No. 1 - fields intensities of von Mises stresses σ_v of the shell*

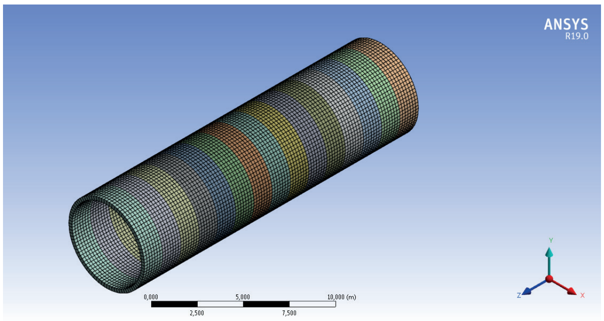

***Figure 2** The mesh of the cylindrical shell tunnel*

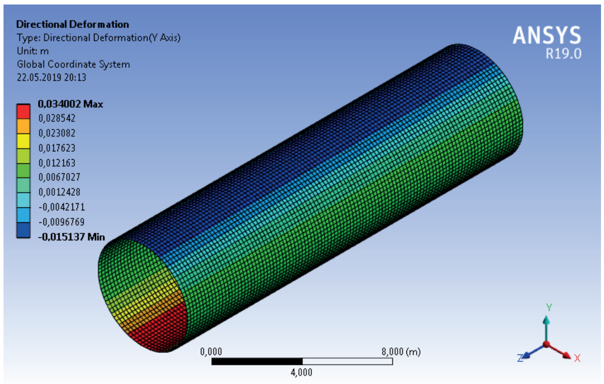

***Figure 4** Computational model No. 1 - fields of vertical displacements of the shell*

When modeling similar designs, it is necessary to work out the equilibrium equations, taking into account change of a shape and sizes of research objects. The ANSYS software package allows to take into account the following nonlinearity: large deformations, large deflections, changes in the effective bending stiffness and effective rotational stiffness.

Physical nonlinearity is shown by nonlinear connections between components of the generalized tensions and deformations and characterizes the work of design material in nonlinearly elastic and plastic stages of deformation.

Constructive nonlinearity needs to be considered as the shell enters the work step by step and during this process can be with or without contact with the soil environment. The contact was defined as contact pairs between the shell and the soil environment with the ability to split and slip between objects [3].

3. Computational model No. 1 does not take into account changes in time

For the first calculation model (without taking into account change of the calculation model in time) calculation was carried out in two stages: determination of the stress-strain state of the isotropic uniform massif in a household state (under the influence of a body weight) and after construction of the whole cylindrical shell in the body of the massif [4].

In Figure 3 are shown the maximum equivalent stresses according to the IV strength theory (von Mises), [5]. The maximum stress was 42.2 MPa, minimum was 429.1 Pa.

In Figure 4 are shown the vertical displacements of a shell, whose maximum values were 0.034 m (shell displacements were cleared after the first stage of calculation).

4. Computational model No. 2 taking into account changes in time

For the second computational model (taking into account the change of the calculation model in time), calculation was carried out in sixteen stages: determination of the stress-strain state of the isotropic uniform massif in a household state (under the influence of a body weight) and after construction of each separate ring of the cylindrical shell in the body of the massif.

In Figure 5 are shown the maximum equivalent stresses according to the IV strength theory (von Mises). The maximum stress was 65.1 MPa, minimum was 744.9 Pa.

In Figure 6 are shown the vertical displacements of a shell, whose maximum values were 0.055 m (shell displacements were cleared after the first stage of calculation).

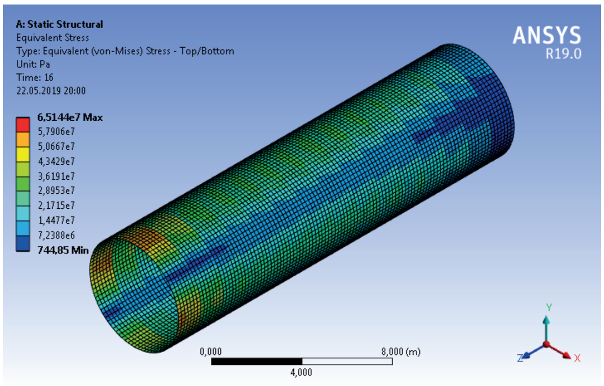

Figure 5 *Computational model No. 2 - fields intensities of von Mises stresses* σ_v *of the shell*

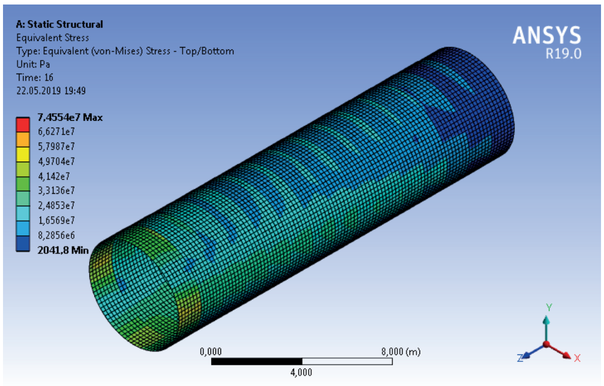

Figure 7 *Computational model No. 3 - fields intensities of von Mises stresses* σ_v *of the shell*

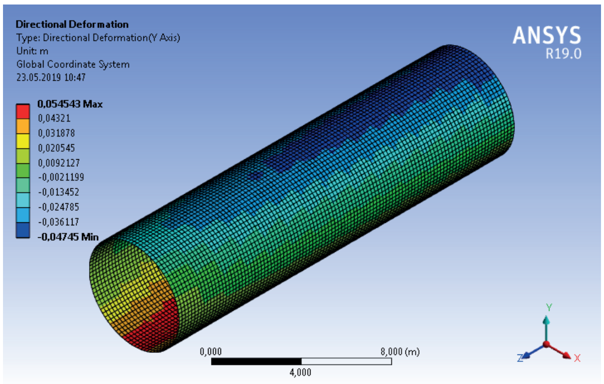

Figure 6 *Computational model No. 2 - fields of vertical displacements of the shell*

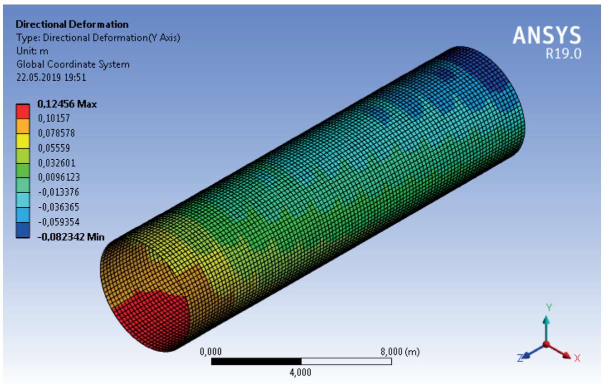

Figure 8 *Computational model No. 3 - fields of vertical displacements of the shell*

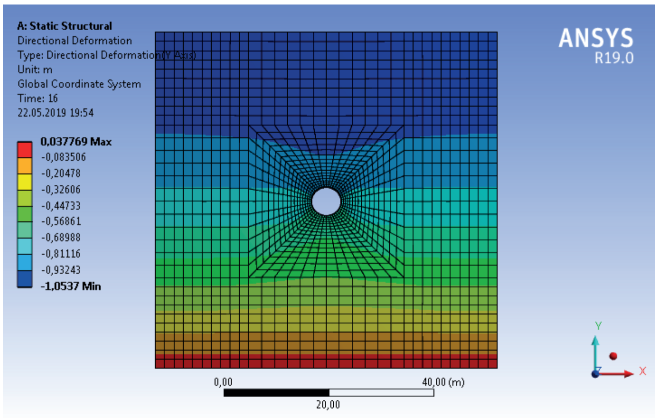

Figure 9 *Computational model No. 3. Fields of vertical displacements of the soil massif*

5. Computational model No. 3 taking into account changes in time and construction gap

In the third computational model the construction gap between the tunnel shell and the soil massif was additionally considered. During the work of a tunnel powered complex (slurry shield), in a face of a tunnel the excess soil is displaced, owing to what the amount of the withdrawn soil always exceeds the theoretically counted quantity, proceeding from a longitudinal profile of a tunnel. This additionally withdrawn soil carries the name “the lost volume”. In order to count “the lost volume” in computational model, the gap between a tunnel shell and the soil massif which volume was equal to the volume of additionally withdrawn soil, was created. Such a model most plausibly reflects the stress-strain state of the soil environment.

In Figure 7 are shown the maximum equivalent stresses according to the IV strength theory (von Mises). The maximum stress was 74.6 MPa, minimum was 2041.8 Pa.

In Figure 8 are shown the vertical displacements of a shell, whose maximum values were 0.125 m (shell displacements were cleared after the first stage of calculation).

The special attention should be paid to characteristic change of the deformed view of the soil massif - it is possible to observe formation of subsidence trough on the top surface of the massif, what is confirmed by the experimental data when passing tunnels by means of a tunnel powered complex (slurry shield).

***Table 1** Summary table of calculation results*

Characteristic	Computational model No. 1	Computational model No. 2	Computational model No. 3
von Mises stress σ_v (Max/Min)	42.2 MPa/ 429.1 Pa	65.1 MPa/ 744.9 Pa	74.6 MPa/ 2041.8 Pa
Vertical displacements of the shell	0.034 m	0.055 m	0.125 m

6. Comparative analysis of the stress-strain state of computational models

Calculation results are presented in Table 1. Equivalent stresses σ_v according to the IV strength theory (von Mises) are more preferable in the current analysis because the shell is experiencing a combined stress-strain state. They are determined by the following formula [6]:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \qquad (1)$$

where σ_1, σ_2, σ_3 - principal stress.

In Figure 9 fields of vertical displacements of the soil massif are shown.

Now, the attention is devoted to a significant increase in displacements of a surface of the soil massif over a tunnel shell in the third computational model, which considers a construction gap between the tunnel shell and the soil massif.

Such a behavior of the soil massif describes the generalized semi-empirical method of determination of subsidence trough of the land surface, for the case of construction of a single tunnel in uniform soils, which was offered by Attewell and Woodman [7-9]. Subsidence trough of the land surface, which is formed as a result of the tunnel construction, can be described by dependence:

$$S = \frac{V_s}{\sqrt{2\pi} i_x} e^{-\frac{x^2}{2i_x^2}} \left[G\left(\frac{y - y_i}{i_x}\right) - G\left(\frac{y - xy_f}{i_x}\right) \right] \qquad (2)$$

where S is the size of displacements of the land surface at a point (x, y); x is the distance from the considered point to the tunnel longitudinal; y is the point coordinate on the tunnel longitudinal; V_S is the net volume of subsidence trough of the land surface; y_i is an initial position of a tunnel; y_f is location of a tunnel face; i_x is width of subsidence trough, i_x=kZ; k is the dimensionless constant that characterizes soil parameters; Z is the distance from the Earth's surface to the tunnel longitudinal axis, [10].

Thus, the third computational model is closer to reality and it reflects behavior not only of a tunnel shell, but of the soil environment a tunnel shell, as well.

It should also be noted that emergence of a construction gap between a shell and the soil massif in the third computational model was carried out step by step - the construction gap appeared together with emergence of the corresponding ring of a tunnel shell.

7. Conclusions

Having carried out calculation of the stress-strain state for three computational models – with or without taking into account changes in time and also taking into account a construction gap between the tunnel shell and the soil massif the following conclusions can be drawn:

- Computational model taking into account changes in time gave significant changes in value of the internal forces in the shell. Obtained equivalent stresses, according to the IV strength theory (von Mises), by the second computational model, in which change of computational model in time was considered, were about 54% higher than values obtained by the first computational model, which was carried out without taking into account the changes of computational model in time. Obtained equivalent stresses, according to the IV strength theory (von Mises), by results of the third computational model, in which change of computational model in time and construction gap between the tunnel shell and the soil massif was considered, were about 76% higher than values obtained by the first computational model. Obtained values of the vertical displacements of the tunnel shell, by results of the second computational model, were for about 2.1 cm bigger that values obtained from the first computational model. Obtained values of the vertical displacements of the tunnel shell, by results of the third computational model were for about 9.1 cm bigger than values obtained from the first computational model.
- Taking into account changes in computational model over time has led not only to a significant change in values of internal forces in a shell, it also led to redistribution of those forces on a shell, what essentially changes principle of work of a shell. In addition, the computational model taking into account its change in time makes it possible to estimate the stress-strain state of a shell in each separate ring.
- Accounting of a construction gap allows to reflect behavior not only of a tunnel shell, but also the soil environment a tunnel shell. It is caused by emergence of subsidence trough on the surface of the soil massif.

According to the above said, when determining the stress-strain state of artificial constructions, whose construction is carried out in several stages (installation of bridge spans, installation of tubing of main line tunnels, etc.), it is desirable to consider all the stages of installation of designs when developing computational model, as this approach allows to obtain more correct values of internal forces in the considered object and distribution of those forces is closer to the real one. Calculations of the stress-strain state taking into account change of computational model in time need to be introduced intensively in design of the building constructions.

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