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# The parametric analysis of the supported circular working interacting with the layered massif

**Ahmad Alkhdour[1], Anatolii Radkevych[2], Oleksii Tiutkin[2] and Nataliia Bondarenko[2,3]**

[1]Al-Balqa` Applied University, Department of Civil Engineering, Al-Salt, 19117, Jordan
[2]Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryan Str., 2, Dnipro, 49010, Ukraine

[3]Corresponding author: tasha.zirka@gmail.com

**Abstract.** The underground construction is based on effective and rapid building of running tunnels that connect stations. The most effective technique of building is shield-driven tunneling. It is based on the application of a tunneling shield, it means, a special aggregate that excavates the ground and builds support. Even with the fact that it holds a surrounding massif, in the weak and layered rocks it is possible the formation of subsidence trough, namely, significant deformations of the daylight area. The solution of this geomechanical problem is possible on the basis of the parametric analysis of the supported circular working interacting with a layered massif. The results of the parametric analysis allow to predict deformation in the "tunneling shield – support of tunnel – surrounding massif" system. For the parametric analysis, the authors use a numerical method of finite elements based on the complex Structure Computer-Aided Design. The calculations of six supported workings with a variation of the properties of a layered massif are carried out. The results of the stress-strain state allow introducing the matrix of parameters into the prediction calculations, enabling quickly and effectively analyze the possible change in the material of support and provide recommendations for the technology of shield-driven tunneling.

## 1. Introduction

Today in the world when the underground construction, shield-driven tunneling in various, especially complex engineering-geological conditions, is the most effective and appropriate method in the building of running tunnels [1-3]. This is due to the fact that the essential foundations of the shield-driven tunneling are based on taking into account the interaction of support with the surrounding massif, providing a high pace of tunneling and the construction of the support at a high safety level of works [3]. But it should also be noted the peculiar features in the tunneling shield associated with the conditions of the support/soil body interaction, compiled by weak, heterogeneous, and layered soils [1, 4, 5].

There is no doubt that the tunneling shield minimally affects the surrounding soil body, in which the technology is being implemented. The process of building support of circular contour occurs under the protection of the tail shell of the tunneling shield while combining with the soil excavating and unloading. This is the reason for the minimum deformation of the massif and the ground surface [3]. However, in the case of a weak layered massif, which has increased deformation capacity, the sizeable subsidence trough is formed on the ground surface [2, 5], which is not always permissible. The emergence of a trough may be associated with soil conditions, when drift sand masses, even in the presence of special devices of the tunneling shield, penetrates into its middle and causes significant deformations of the surface [5].

The most important role in the geomechanical analysis of the stress-strain state (SSS) in the "tunneling shield – support of running tunnel – surrounding massif" system plays accountability and the interaction of three parts in this system [6, 7]. The behavior of layered and weak soils under load has been studied in sufficient detail, but a single analytical approach is still not being introduced, it is explained by a significant spectrum of soil conditions and interactions that arise in the development of the SSS in the massif of weak and layered rocks.

This is explained, on the one hand, the difficulties of studying the systems of defined humidity and the lithological composition, and on the other hand, the limited observation in the behavior of a layered massif while tunneling [7, 8]. However, the presence of such predictive information in some cases is on the front burner, since the change in the deformation properties of soils, which may be unpredictable, requires operational action [7, 9, 10]. The method of predictive calculations, except the usage of the general theoretical provisions of geomechanics and the constructing appropriate calculation schemes, has a pronounced specific character due to the features of engineering-geological, hydrogeological, and mining-technological conditions for the construction of the underground facilities.

It is necessary to develop a special strategy of work that will allow, having a significant complex of projection data, to envisage potential scenarios of the SSS change in the "tunneling shield – support of running tunnel – surrounding massif" system. An instrument of such a predictive strategy is the parametric analysis of the supported working, which is a running tunnel of underground interacting with a layered soil massif. The purpose of this study is to develop the basics of such an analysis that allows you to quickly and effectively analyze the possible change in the material of support and provide recommendations for the operational change in the technology of shield-driven tunneling.

## 2. Methods

Currently, there are three main directions in the development of methods of predictive calculations based on various techniques of researching processes accompanying the underground construction: 1) empirical, using the results of instrumental observations and their statistical processing [7]; 2) analytical, resting on closed solutions to the problems of geomechanics and mechanics of rocks [7, 9]; 3) numerical, built on structural analysis and solutions of the continuum mechanics [2, 10].

Parametric analysis refers to the third method of research since it is based on the finite-elements method and in its essence associated with performing the multiple numerical calculations in the "tunneling shield – support of running tunnel – surrounding massif" system with single parameters. Methodologically, it is realized as a system solution of actions: 1) Scaling of SSS in solving the problem with single parameters; 2) using the matrix of parameters with regard to the transition from one material of support to another.

It is known that in the analytical method of determining the subsidence trough of the land surface caused by tunneling of running tunnels, the Gauss curve is most often used [7, 8]:

$$\eta = \eta_m \exp\left[-\frac{x^2}{2i^2}\right], \tag{1}$$

where $\eta$ – ground subsidence (m) at distance $x$ from tunnel axis (m); $\eta_m$ – the maximum ground subsidence over the tunnel axis (m); $i$ – the abscissa of the inflection point of the subsidence trough curve (m).

By differentiation of dependence (1) formulas were obtained to calculate tilt $j_x$, curvature $k_x$ and radius $R_x$ (m) for the curve of ground subsidence in the cross-section of the subsidence trough:

$$j_x = -\eta_m \frac{x}{i^2} \exp\left(-\frac{x^2}{2i^2}\right), \tag{2}$$

$$k_x = -\eta_m \frac{1}{i^2} \exp\left(-\frac{x^2}{2i^2}\right)\left(1-\frac{x^2}{i^2}\right), \tag{3}$$

$$R_x = -\frac{1}{\eta_m} \cdot \frac{i^4}{(i^2 - x^2)} \exp\left(\frac{x^2}{2i^2}\right). \tag{4}$$

Thus, after searching the values determined by the formulas (1) - (4), and comparing the indices with the limiting values of the subsidence trough, there is a possible scenario of the transition from the reinforced concrete support of the running tunnel to cast-iron one. This step is explained by the fact that support from cast-iron tubbings is characterized by a greater value of the elasticity modulus and, accordingly, smaller deformations. This logical step, although requires additional projection, significantly improves the situation of deformation of a weak layered massif, reducing the magnitude of the subsidence trough.

Unlike an analytical approach at the parametric analysis, the values of SSS in the "tunneling shield – support of running tunnel – surrounding massif" system may only be obtained after the parametric analysis using the two-step algorithm. Each step is responsible for transforming the SSS in finite-element models and is associated with the operating of special parameters. At the same time, it is possible to obtain SSS for the case of cast-iron support in the presence of calculated stresses and displacements for support from reinforced concrete.

Step 1. The SSS calculation for the working with a single radius $r$ and scaling [10] of displacements and stresses for a case of specific radius $R$. In the course of such calculation a thickness of support $h$ should be constant, and the elasticity modulus value $E$ of support is equal to the value for reinforced concrete.

Step 2. Multiplications of displacements and stresses in the characteristic points of support (point 1 – vaults, point 2 – a point on the horizontal diameter, point 3 – tray, figure 1) on the matrix of parameters, which is constant for all radii for working $R$. Throughout this mathematical action of the displacements and stresses obtained for support from reinforced concrete, turn into the same indices, but for the cast-iron structures.

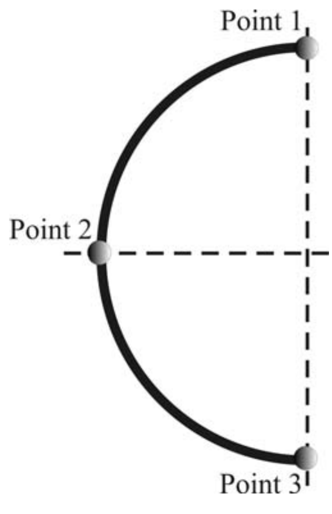



**Figure 1.** Scheme of characteristic points on the contour of the supported working.

Thus, using the parametric analysis, it is possible to promptly evaluate the situation of changing the properties of a layered massif and change the material of support with the prediction in the change of SSS in this case.

To obtain this solution, the finite-element method in the software package StructureCAD (SCAD) was applied (license number F755B84 (KMBKB RA 4810)). Finite element model is spatial on the basis of solid finite elements, the number of nodes – 97240, final elements – 48196. Model dimensions: height – 22 m, width – 22 m, thickness – 0.1 m. In the model of rock massif (elasticity modulus of matrix $E_m$ = 30 MPa) a hole was made with radius $R$ and a layer of weak soil (elasticity modulus of a layer $E_s$ = 30 MPa).

Support, applied in the model, had a thickness $h$, equal to 0.1 m (figure 2).

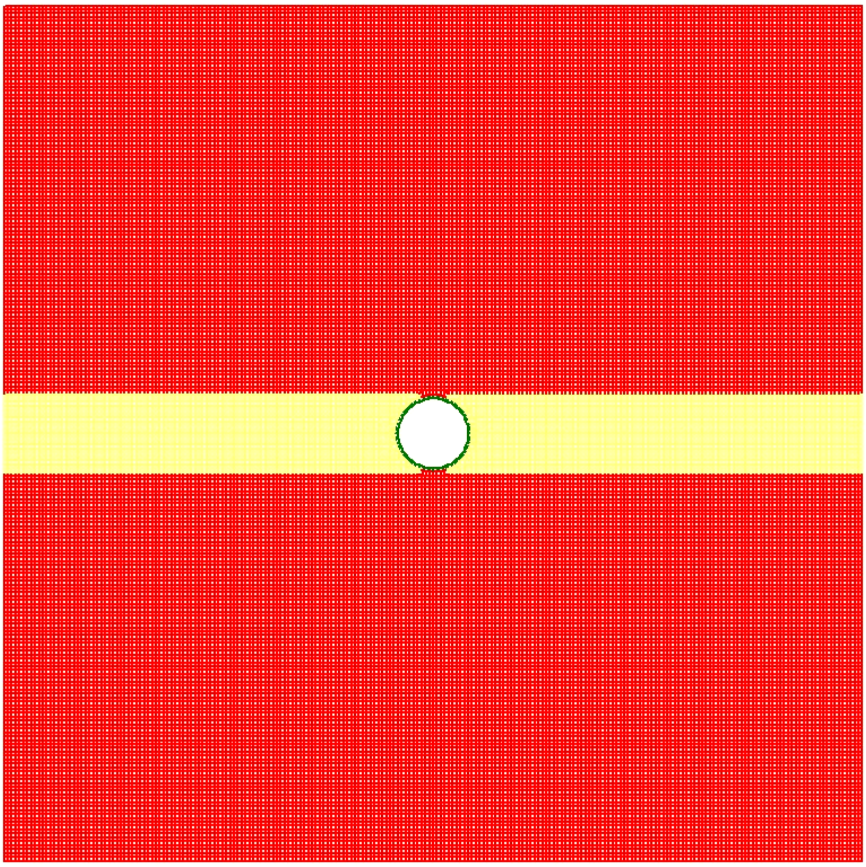


**Figure 2.** A finite-element model of the supported working, radius R with support, thickness h, which lies in a layered massif.

To confirm the authors' ideas, six finite element models of geomechanical systems "support of a running tunnel – surrounding massif": three with support, thickness is of 0.1 m, variable radius ($R_1$ = 1.0 m; $R_2$ = 5.0 m; $R_3$ = 10.0 m) and elasticity modulus of reinforced concrete $E = 32.5 \cdot 10^3$ MPa, three with support, thickness is of 0.1 m, variable radius ($R_1$ = 1.0 m; $R_2$ = 5.0 m; $R_3$ = 10.0 m) and elasticity modulus of cast-iron $E = 20.1 \cdot 10^4$ MPa.

## 3. Results and discussion

The calculation of the finite-element models was performed with the decomposition of the matrix by the multifrontal method. Figures 3 and 4 show the characteristic isolines and isofields of vertical displacements $z$ (mm) and vertical stresses $N_z$ (kN/m$^2$) of fragments of two finite-element models (results for the third model, as well as isolines and isofields of horizontal displacements $x$ (mm) and horizontal stresses $N_x$ (kN/m$^2$), which were also analyzed, are not presented to save space in the article).

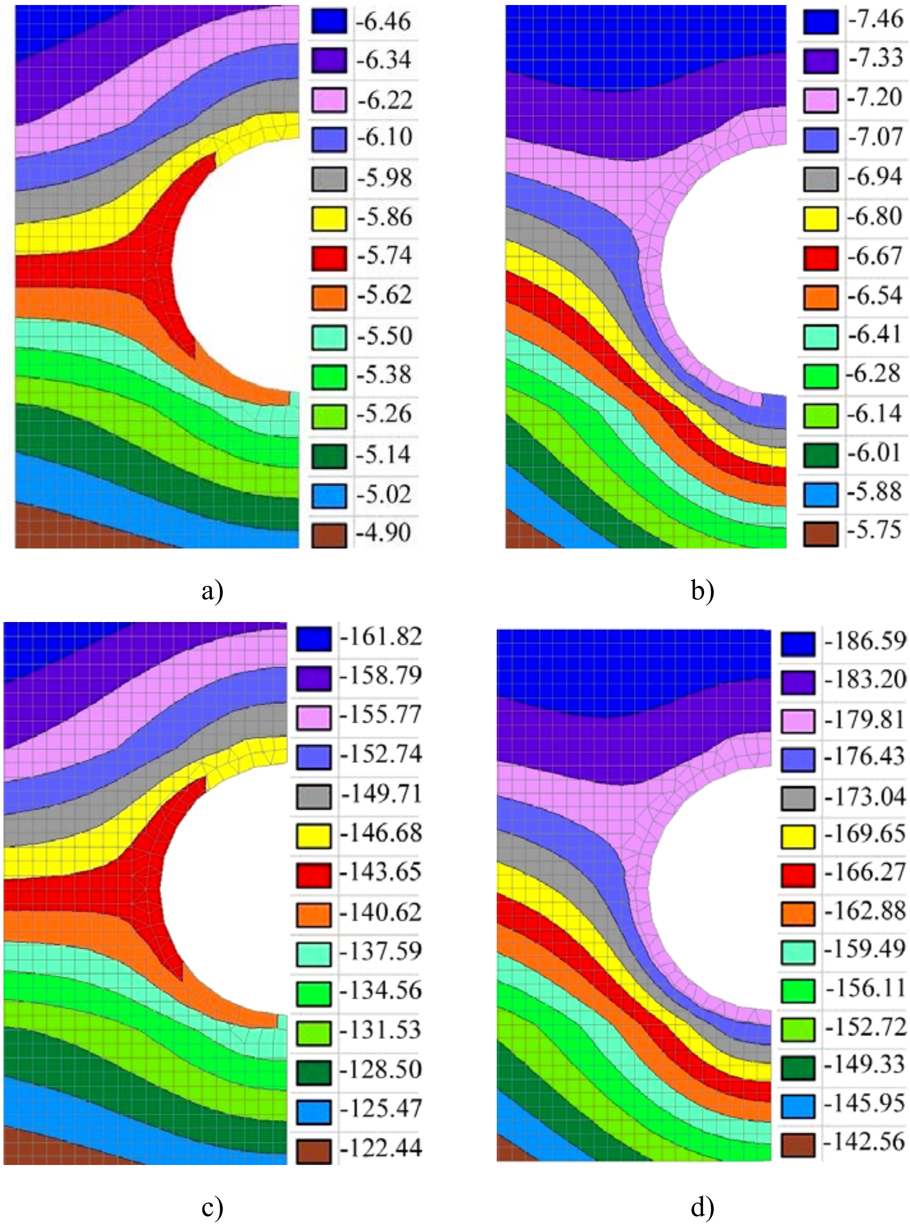
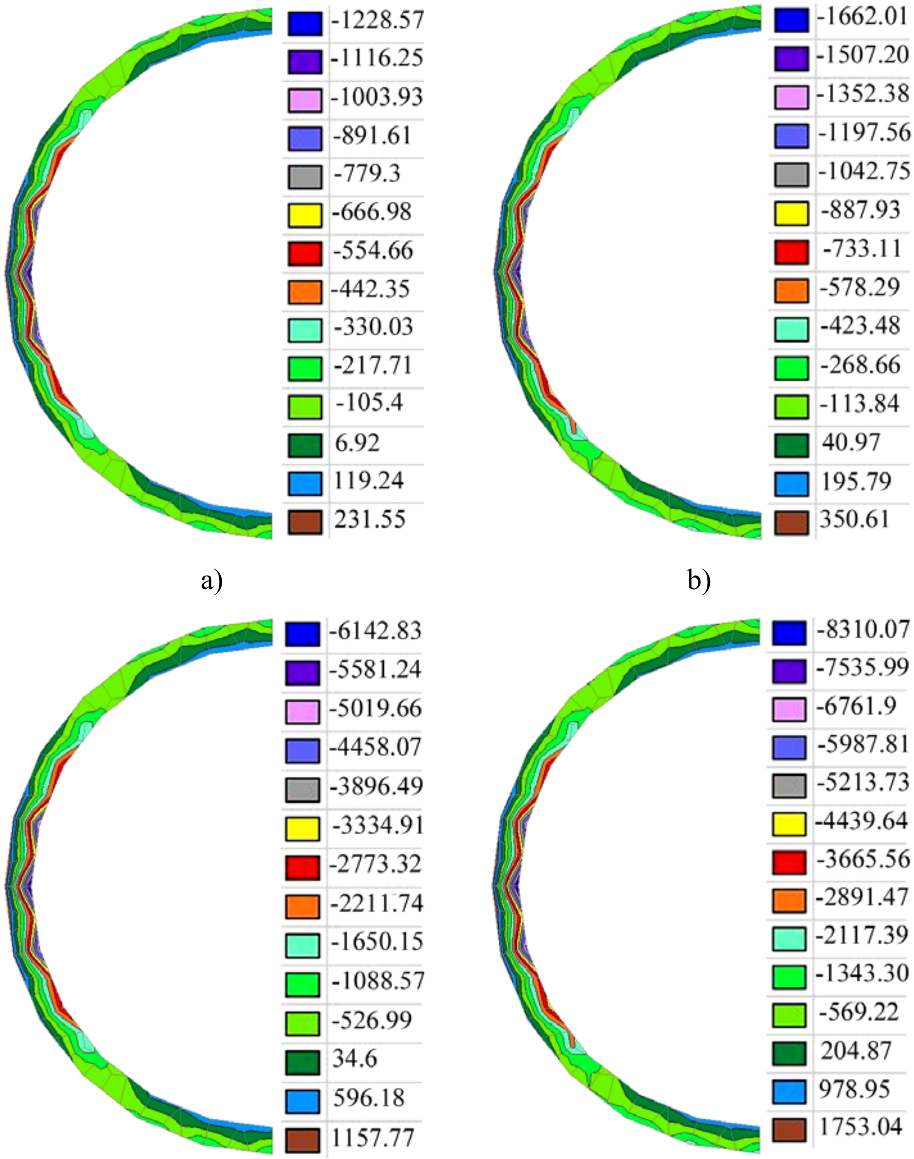



**Figure 3.** Isolines and isofields of vertical displacements z (mm) in fragments of finite-element models: a) radius of working $R_1 = 1.0$ m, reinforced concrete support with a thickness of 0.1 m; b) radius of working $R_1 = 1.0$ m, cast-iron support with a thickness of 0.1 m; c) radius of working $R_2 = 5.0$ m, reinforced concrete support with a thickness of 0.1 m; d) radius of working $R_2 = 5.0$ m, cast-iron support with a thickness of 0.1 m.

The qualitative difference in the distribution of vertical displacements $z$ (mm) for supports with different material (figure 3, a and b, c and d) is explained by the impact of elasticity modulus of the matrix/layer and structure relationship, the quantitative analysis indicates about an unambiguous effect of harsher from them (cast-iron support with a thickness of 0.1 m). If we analyze figure 4, it can be noted that the qualitatively vertical stresses $N_z$ (kN/m$^2$) does not change, therefore, the quantitative analysis of values in characteristic points do not cause difficulties. The matrix of parameters with which one can find the SSS of the cast-iron support in its three characteristic points (figure 1), having displacements and stresses in the reinforced concrete one, is shown in table 1.




a) b)

c) d)

**Figure 4.** Isolines and isofields of vertical stresses $N_z$ (kN/m$^2$) in fragments of finite-element models: a) radius of working $R_1 = 1.0$ m, reinforced concrete support with a thickness of 0.1 m; b) radius of working $R_1 = 1.0$ m, cast-iron support with a thickness of 0.1 m; c) radius of working $R_2 = 5.0$ m, reinforced concrete support with a thickness of 0.1 m; d) radius of working $R_2 = 5.0$ m, cast-iron support with a thickness of 0.1 m.

**Table 1.** The matrix of parameters.

| SSS parameter | Point 1 | Point 2 | Point 3 |
|---|---|---|---|
| Horizontal displacements $x$, mm | 0 | 0.22 | 0 |
| Vertical displacements $z$, mm | 1.23 | 1.25 | 1.28 |
| Horizontal stresses $N_x$, kN/m$^2$ | 1.47 | 1.44 | 1.47 |
| Vertical stresses $N_z$, kN/m$^2$ | 1.47 | 1.35 | 1.47 |

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For the maximum operational prediction calculations, it is possible to create a software complex that will have a database for potential indices of the elasticity modulus of the soil matrix and a layer, their relationship, as well as the values of the reinforced concrete support. Such a complex will enable while the shield-driven tunneling to evaluate the deformed state of the massif and the size of the subsidence trough and recommend changing the material of support to cast-iron using the matrix of parameters.

## 4. Conclusions

In the course of the conducted research, the regularities of changing SSS in supported workings, which are laid down in a layered massif are determined. They allowed to obtain the matrix of parameters that extrapolate a solution for the reinforced concrete support for the case of support from cast-iron. An algorithm of the parametric analysis of two steps is developed, enabling to calculate supported workings of various radii, using a system with a single parameter and scaling process.

Although an obtained solution is closed to a problem setting that has been posed, in the future it should be used for systems with different stiffness of support. The resulting matrix of parameters, when using for supports with changing not only the elasticity modulus of the material, but a thickness, will allow the conduct of even more operational calculations for an effective shield tunneling.

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