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Substantiating the parameters for a non-circular structure of the mine shaft under construction in a heterogeneous rock massif

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Abstract. Mine shafts are those workings without which the normal operation of coal enterprises and underground construction facilities is impossible. The new experience in the construction of mine shafts for the Dnipro Metro is based on the rejection of prefabricated structures. In addition, the ellipse structure of the mine shaft 15 bis of the Dnipro Metro is uncharacteristic for construction in Soviet and post-Soviet Ukraine. That is why technological advancements in the design of vertical workings for the non-circular structure require scientific justification. The complexity of operating such underground facilities under the engineering and geological conditions in the city of Dnipro is the interaction with a heterogeneous massif. Therefore, the design of the mine shaft frame involves its division into parts (the so-called pile system and shotcrete system). The finite-element models of both systems have been developed. A search for the force factors in a non-circular structure of the shaft has been carried out; the parameters for both systems have been substantiated. The results of the analysis have made it possible to scientifically substantiate the structural solutions. They enable the prediction of high strength indicators of the mine shaft under construction in a heterogeneous rock massif.

1. Introduction

Mine shafts are the primary vertical mine workings that make it possible to start a cycle of basic operations. In the development of minerals, the task of a mine shaft is to open the front of work on the construction of a system of preparatory and breakage headings [1]. In underground construction, for example, when building a subway, the mine shaft is the working that enables the rapid exchange of materials and labor [2]. Accordingly, the operation of the mine and the site for the construction of underground facilities depends on how fully the shaft design is justified.

Before the start of the military invasion of the Russian Federation against Ukraine, the underground construction of subways in this country reached a new stage. That was especially noted during the construction of the Dnipro Metro (as of February 24, 2022, the activities were suspended during martial law) since the representative office of the Turkish company LIMAK Insaat Sanayi Ve Ticaret AS had been actively implementing its advancements since 2016. Thus, the Soviet experience of constructing vertical (mine shafts), horizontal (interstation tunnels, station workings), and inclined (escalator tunnels) facilities, based on the use of prefabricated elements, was revised.

It should be noted that the conceptual basis of LIMAK is focus on building multilayer monolithic structures and, accordingly, the widespread use of the New Austrian tunneling method (NATM) [3–4]. Significant experience of LIMAK specialists and sufficient development of NATM in practical and theoretical aspects made it possible to solve a wide range of tasks related to underground construction. During the introduction of technological advancements, it was necessary to implement new experiences, which led to the revision of the old, Soviet experience, in which "wet" processes (monolithic concreting, application of shotcrete, construction of multilayer structures) were minimized. Such a revision of the construction strategy and the restructuring of the approach to underground construction are objective. The arguments are that the prefabricated elements for any workings are now almost not made while increasing the culture of concreting enables the construction of temporary fasteners and permanent frames with high quality (figure 1).

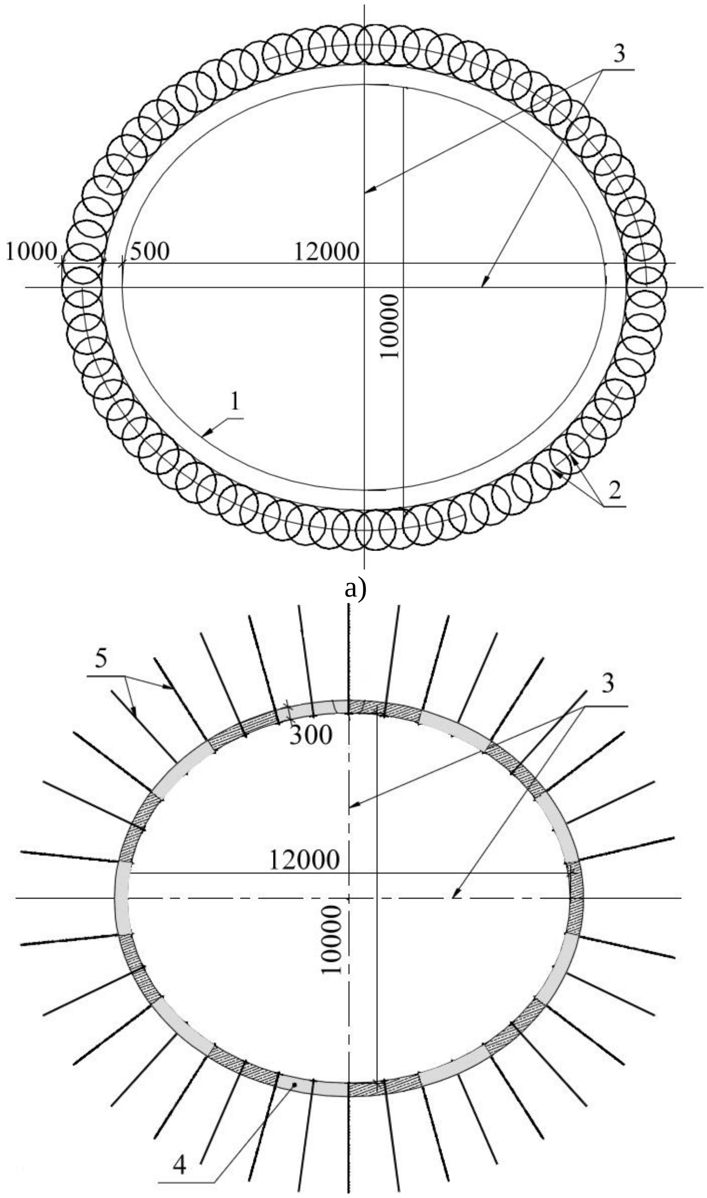


Figure 1. Cross-section of the shaft 15 bis: a) pile system; b) shotcrete system; 1 – ring beam; 2 – bored piles; 3 – axis of construction shaft 15 bis; 4 – shotcrete; 5 – rock bolts.

The structure of the mine shaft 15 bis, used during the construction of the Dnipro Metro, is uncharacteristic for construction in Soviet and post-Soviet Ukraine (figure 1). Differences from the known structures of mine shafts are the ellipsoidal cross-sectional shape and the construction of a shaft frame with division into parts (the so-called systems). The shape, which is different from a circle, is explained by the need to open the widest possible front of underground operations since such a working allows machines and mechanisms to be delivered to the site in an unassembled form while the unloading of rock does not require a mining complex and is carried out with the help of a bucket and a crane.

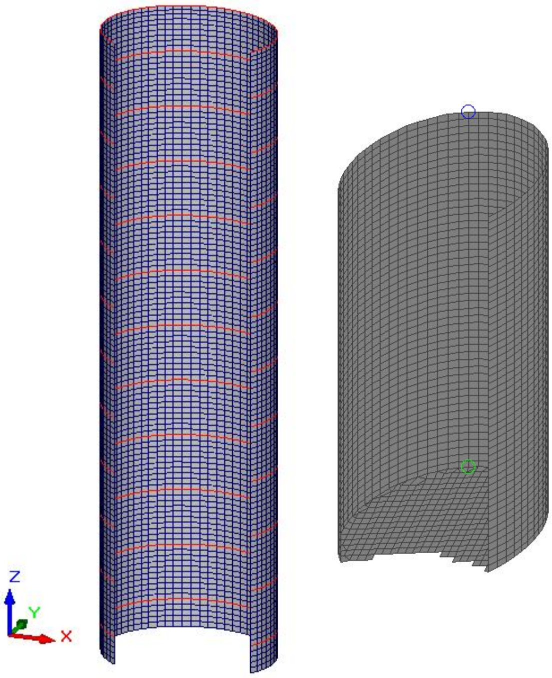
The division of the workings into parts is based on the analysis of engineering and geological conditions, namely on the presence of a heterogeneous massif. The first part ("pile system", figure 1, a) is located in weak soils and is arranged from bored piles [5]. As proved by practical experience, the use of such elements eliminates the need to use special methods of construction (for example, freezing soils) [6]. The second part ("shotcrete system", figure 1, b) is located in rocks (gray plagiogranite) and is constructed by shotcrete and strengthening the surrounding massif with rock bolts [7]. The presence of such systems for the heterogeneous massif of Dnipro is inherent not only in vertical but also horizontal [8] and inclined workings [9], which also require a detailed study of such a difficult case.

The purpose of the research, the results of which are reported in this paper, is to substantiate the parameters of the design systems for the mine shaft 15 bis, which interacts with a heterogeneous massif. To this end, a method of finite elements was used to find force factors in the non-circular shaft design; the parameters for both systems have been substantiated.

2. Methods

The research of two systems of the structure of the mine shaft 15 bis, which interacts with a heterogeneous massif, is carried out in parts. This is a valid methodological step since the two shaft systems are not connected and do not affect each other.

For simulation, a finite-element method implemented in the SCAD (license number F755B84 (KMBKB RA 4810)) software package was adopted [10]. For both systems, the cross-section of the shaft and its dimensions are in light of 14.0×12.0 m, so both models were built from a flat prototype and are spatial (figure 2).



a) b)

Figure 2. Fragments of the finite-element models (shells) of the shaft 15 bis (SCAD software): a) pile system (reinforced concrete belts and a strapping beam are shown in red); b) shotcrete system (blue circle shows the beginning of the fastening and its connection with the concrete slab is shown in green).

The total depth of the shaft 15 bis is 74.36 m (depth of the pile system, 50 m; depth of the shotcrete system, 23.36 m; belt thickness, 1.0 m). In the design of the pile system, the arrangement of eleven reinforced concrete belts with a cross-section of 0.5×0.5 m and a strapping beam with a cross-section of 1.0×1.2 m (figure 3) is implied. The belts are placed at the following distances from the strapping beam: 3.74 m (ring beam No. 1) and 4.5 m (ring beams No. 2-11).

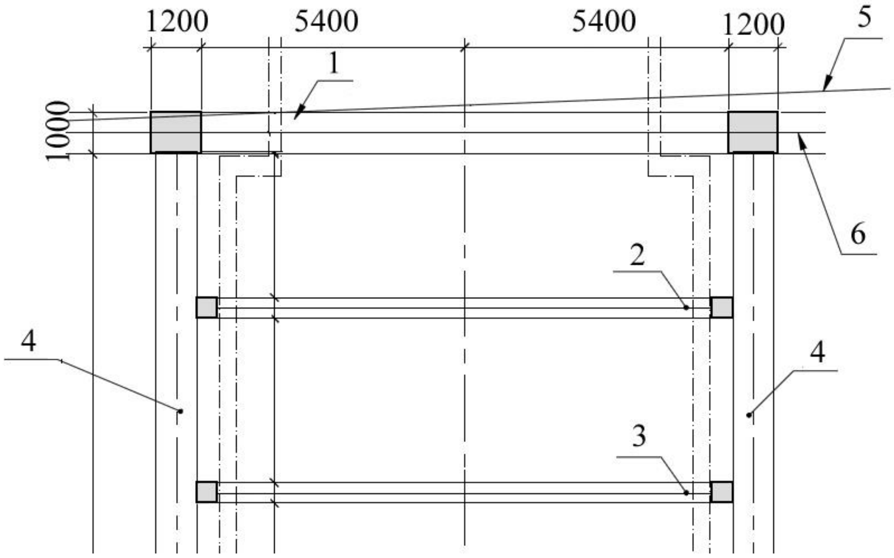


Figure 3. Fragment of the shaft 15 bis: 1 – cap beam; 2 – ring beam 1; 3 – ring beam 2; 4 – bored piles; 5 – natural elevation level; 6 – project elevation level.

The frame of both systems is modeled with plates; belts and a strapping beam – with rods. Thus, the height of the finite element is taken to be 0.45 m; two plate-rod models of the shells of two 15 bis construction shaft systems are built. The plates and rods of the finite-element models are assigned a modulus of elasticity of $32.5 \cdot 10^3$ MPa and an estimated compressive resistance of 15.5 MPa. The same strain characteristics are assigned to the plates of the shotcrete system with a thickness of 0.3 and 0.35 m (concrete B30; modulus of elasticity, $32.5 \cdot 10^3$ MPa). The concrete slab of the base of the shotcrete system with a thickness of 0.25 m is also simulated by plates.

Loads are applied to both models of the shaft 15 bis: 1) the natural weight of the bored pile system/the natural weight of the shotcrete system; 2) load from the surrounding soil q_h; 3) hydrostatic load q_w; 4) temporary load from the crane q_c. Only 1 and 2 loads are applied to the finite-element model of the shotcrete system since the plagiogranite is water resistant while the effect of the load from the crane at a considerable depth fades. The load from the surrounding soil for the pile system is calculated as an active horizontal pressure for weak soils lying to a depth of 49.1 m:

$$q_h = K_a \gamma H\,, \tag{1}$$

$$K_a = \tan^2\left(45 - \frac{\varphi}{2}\right), \tag{2}$$

where q_h is the horizontal pressure, kN/m^2; K_a is the coefficient of active pressure; γ is the soil specific gravity, kN/m^3; H is the depth of embedding, m; φ is the angle of internal friction, degree.

The load on the shotcrete system is determined for plagiogranite as passive, which is characteristic of rocks. The calculation of two finite-element models of the system of the combined structure of shaft 15 bis is carried out on a combination of loads with the corresponding coefficients using the SCAD software package.

3. Results and discussion

The results of the numerical analysis have made it possible to find the force factors in the shells of the pile system (figure 4) and the shotcrete system (figure 5).

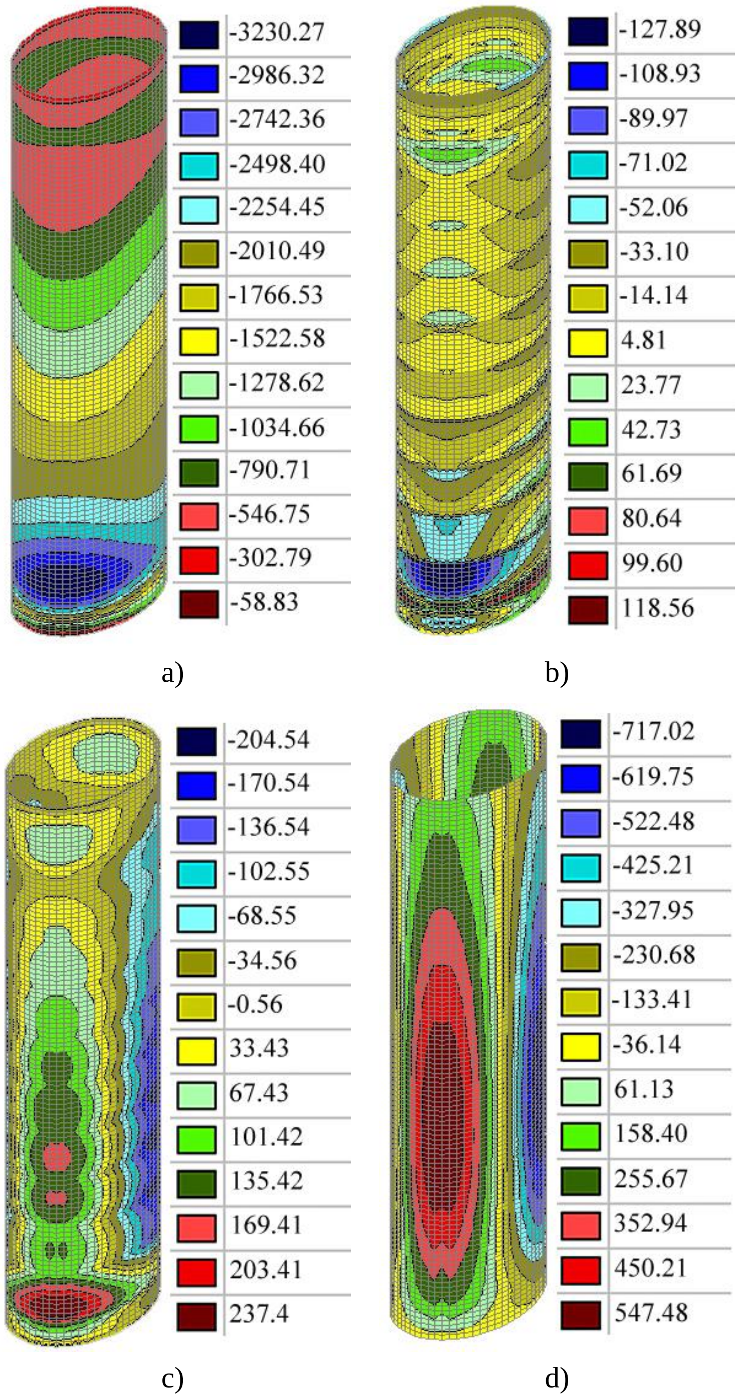


Figure 4. Force factors in the pile system of the shaft 15 bis: 1) normal forces (the X-axis), kN/m; 2) normal forces (the X-axis), kN/m; 3) bending moments (the X-axis), kN·m/m; 4) bending moments (the Y-axis), kN·m/m.

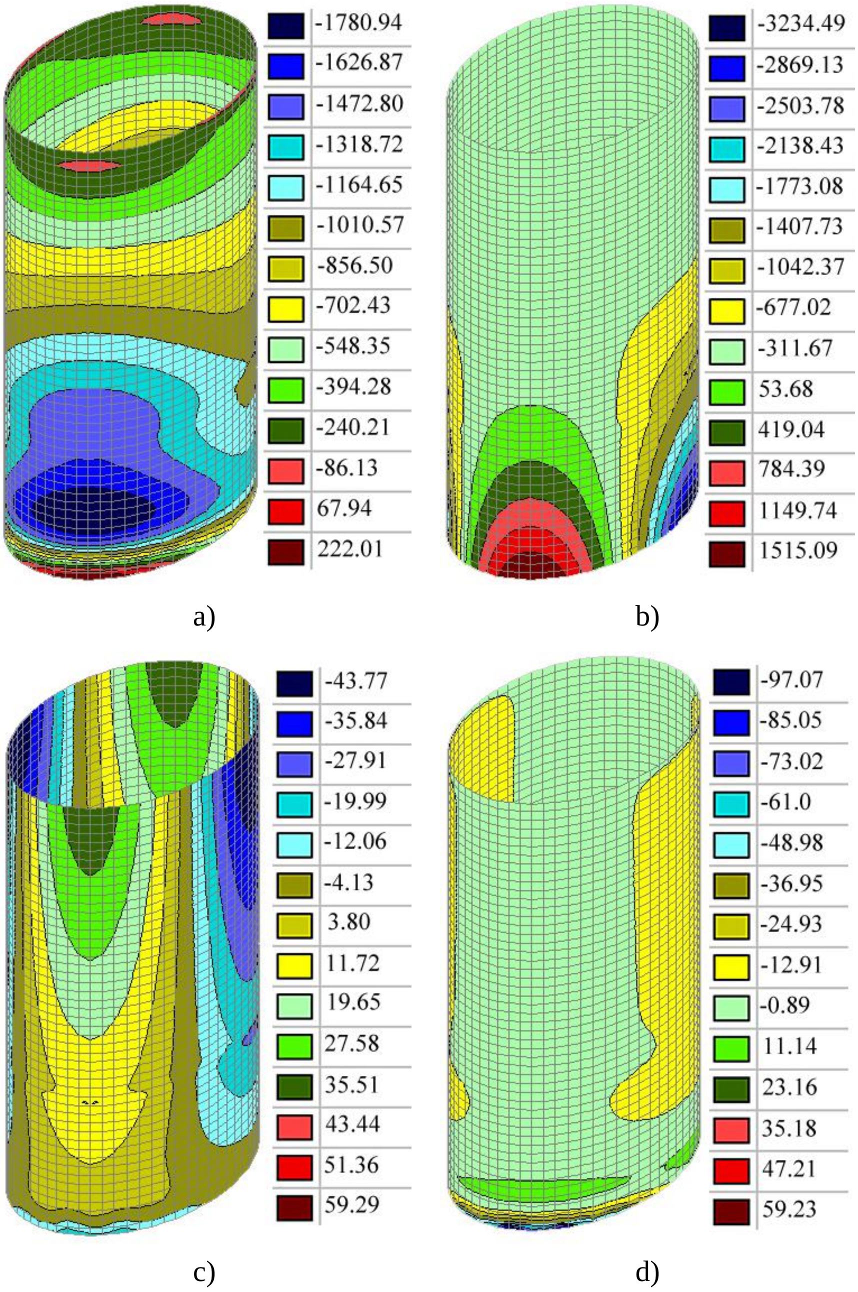


Figure 5. Force factors in the shotcrete system of the shaft 15 bis: 1) normal forces (the X-axis), kN/m; 2) normal forces (the X-axis), kN/m; 3) bending moments (the X-axis), kN·m/m; 4) bending moments (the Y-axis), kN·m/m.

Based on the isolines and isofields of force factors (figure 4), their maximum values in the pile system were determined: normal forces (the X-axis) – -3279.6 kN/m (in the region of the reinforced concrete belt No. 11); normal forces (the Y-axis) – -3964.2 kN/m (lower part of the pile system); bending moments (the X-axis), negative – -737.5 kN· m/m, positive – 663.0 kN·m/m (in the region of reinforced concrete belts Nos. 7–9); bending moments (the Y-axis), negative – -210.3 kN·m/m (in the area of the reinforced concrete belt No. 8), positive – 274.9 kN·m/m (in the region of the reinforced concrete belt No. 11). The maximum values of force factors in the shotcrete system (figure 5) were also determined: normal forces (the X-axis) – -1780.9 kN/m (in the region of transition to the concrete base slab), normal forces (the Y-axis) – -3234.5 kN/m (in the region of transition to the concrete base slab); bending moments (the X-axis), negative – -43.8 kN·m/m (in the region of connection between the pile system and shotcrete system), positive – 67.2 kN·m/m (in the concrete slab of the base); bending moments (the Y-axis), negative – -97.7 kN·m/m, and positive – 71.3 kN·m/m (in the concrete slab of the base).

The maximum force factors in the strapping beam/reinforced concrete belt No. 7 were analyzed: normal force – -108.1 kN/-404.3 kN, bending moments – 187.9 kN·m/39.4 kN·m. Based on these force factors, reinforcement for bored piles of the pile system was calculated, and the total area of reinforcing rods was obtained – 71.52 cm^2, and 24 reinforcement rods of ∅22 class A500C were adopted; and for the shotcrete system – the total area of reinforcing rods is 15.8 cm^2, and 12 rods of ∅12 reinforcements of class A500C (35 cm) with a cell of 150 mm were adopted.

4. Conclusions

This paper substantiates the parameters for a non-circular structure of the mine shaft, which is constructed in a heterogeneous rock massif. This has made it possible to check the designed dimensions of the pile system (pile diameter, cross-sections of reinforced concrete belts and strapping beams, reinforcement characteristics), as well as the shotcrete system (variable thickness of the shell of shotcrete concrete).

In the course of numerical analysis, the method of finite elements of the shaft 15 bis in the Dnipro Metro is used to determine the normal forces and bending moments for both systems. The results of the analysis allow us to scientifically substantiate the structural solutions.

The current research on the design of a mine shaft makes it possible to indicate that the new construction experience, which is based on the principles of NATM, is very fruitful. It requires comprehensive analysis and revision of the conceptual foundations of underground construction in Soviet and post-Soviet Ukraine.

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