ТЕХНИЧЕСКИЕ НАУКИ
TECHNICAL SCIENCES

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ANALYSIS OF THE STRESS-STRAIN STATE OF PROBLEMATIC SECTIONS OF THE SHAFT OF THE MINE USING COMPUTER SIMULATION

Abstract. The article presents the computer simulation results for the stress-strain state of the lining sections of the shaft No. 1 of mine 3 of JSC Belaruskali that were obtained using visual and instrumental investigation of the mine lining state. The loading parameters of the shaft take into account the specific feature of the lateral pressure calculation in the considered location. This means that the shaft intersects vertically rocks different in their physical and mechanical properties. Computer simulation of loading of the most problematic vertical mine shaft sections observed by the lining examination results was performed using the Static Structural component of the ANSYS Workbench engineering software package. Distribution diagrams of longitudinal normal, shear and von Mises equivalent stresses in the vertical mine shaft lining are obtained for the design and residual values of the cast-iron tubing thickness. A comparative analysis of the mine shaft residual bearing capacity for various parameters of the lining elements was carried out. Based on the computer simulation results, the conclusions were made on the bearing capacity of the shaft No. 1 of mine 3 of JSC Belaruskali and the recommendations for a further safe operation of the mine shaft were suggested.

Keywords: vertical mine shaft, rock pressure, stress-strain state, computer simulation, bearing capacity

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АНАЛИЗ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ПРОБЛЕМНЫХ МЕСТ ШАХТНОГО СТВОЛА РУДНИКА НА ОСНОВЕ КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ

Аннотация. Представлены результаты компьютерного моделирования напряженно-деформированного состояния участков крепи ствола № 1 рудника 3 ОАО «Беларуськалий», выполненные на основе визуального и инструментального обследования состояния крепи. Параметры нагружения ствола шахты учитывают особенность расчета бокового давления на рассматриваемом участке, заключающуюся в пересечении вертикальной выработкой различных по своим физико-механическим свойствам горных пород. Компьютерное моделирование нагружения части ствола, в которой наблюдаются наиболее проблемные по результатам обследования крепи участки, выполнено с использованием компаненты Static Structural инженерного программного комплекса ANSYS Workbench методом конечных элементов. Получены диаграммы распределения продольных нормальных, сдвиговых и эквивалентных по Мизесу напряжений в крепи вертикального ствола шахты на самом проблемном участке для проектных и остаточных значений толщин чугунного тюбинга и затюбинговой бетонной крепи. Произведен сравнительный анализ остаточной несущей способности ствола шахты при различных параметрах крепи. На основании результатов компьютерного моделирования сделаны выводы о несущей способности ствола № 1 рудника 3 ОАО «Беларуськалий» и предложены рекомендации по дальнейшей безопасной эксплуатации ствола шахты.

Introduction. The stability of the mine shafts is a key problem of their operation and largely depends on the mechanical properties of the rock array. In many rocks, including salts, the monolithic concrete lining is traditionally used in the shaft construction [1]. Over time, its deformation and destruction takes place due to the constant pressure from the rock masses. Moreover, this pressure gradually increases due to the salt rocks creep without visible destruction of the massif [2; 3].

The most accurate information about the state of the shaft concrete lining and the cast-iron tubing can be obtained only by the experimental way [4], but it is often the complex problem due to the inaccessibility of the great amount of locations for the direct instrumental control [5]. Therefore, nowadays there are many methods for diagnosing the state of mine shaft lining elements, for example, field research [6], GPS monitoring [7], thermo sensors [8], methods of ultrasound tomography and shock echo [9], spectral and deformation analysis of the "shaft-arming" system for the vertical shafts [10], georadiolocation [11], etc. The mentioned methods can effectively provide data on the structures deformation but cannot prevent or predict the destruction of the elements in advance.

One of the perspective ways to evaluate the mine shaft bearing capacity is the computer simulation. In particular, the authors of works [12; 13] offered approaches to computer modeling at vertical mines designing stage. The numerical modeling of the concrete lining loading for the horizontal tunnels, strengthened by metal reinforcement with the experimentally confirmed results are given in [14].

In the investigation [15], there are presented the results of the stress-deformed state analysis for the part of the coal mine cylindrical vertical shaft obtained on the base of a finite-elemental modeling. The continuation of these studies is given in the dissertation [16]. In the study [17], an analysis of the stresses distribution around the vertical shaft of the mine with a 10 m diameter round cross-section under the action of three-dimensional load is carried out using the finite element method.

Thus, the purpose of the presented work is to evaluate the stress-deformed state of the shaft No. 1 of mine 3 of the JSC Belaruskali on the base of the finite element computer modeling considering the peculiarities of the shaft state obtained by its visual and instrumental control, described in [18].

Features of the design and the state of the shaft No. 1 of mine 3. The shaft upper part fastening from 12.6 to 322.54 m is made by the reinforced cast iron tubing type (K-30, K-40, K-50, K-60) with a wall thickness from 30 to 60 mm with a filling of the space around tubing with the M200 concrete. The shaft section between the marks of 322.54 and 615.57 m is fixed by a two-layer monolithic concrete lining with a total thickness of 450 mm. The bottom part of the shaft from 615.57 to 623.8 m is reinforced by the cast-iron tubing with the lead waterproofing and the M200 concrete in the space around the tubing [18].

In accordance with the report [18], the degree of corrosion of the shaft cast-iron tubing is reduced in the direction from the upper layer in the direction of the shaft bottom. The most intensive corrosion is observed in the upper part of the tubing column between 4–40 layers of reinforcement. The defects are the destruction by 30–40 % of the initial size of the tubing walls and the fastening bolts for the tubing sections. An intensive corrosion of tubing lining is also observed in the locations where the underground waters seal thought the joints of tubing sections and the picotage seams (between layers 20–29 and 37–48).

The water sealing through the tubing lining can be characterized as sucking (the formation of wet spots) and dripping. The most intensive water sealing is observed in the location of support crowns No. 3 between layers 28–29 (fig. 1) and No. 4 between layers 37–38 (fig. 2) of the mine shaft lining.

Materials and methods of research. The geometric parameters of the mine shaft correspond to the parameters specified in [18]. Calculations of the lateral pressure on the shaft No. 1 of mine 3 ($H = 623.8$ m) are performed on the basis of geological data from [18] and the formulas given in [19]. The obtained results were used as an initial data for the computer modeling. The external pressure acting from the surrounding rocks on the shaft is calculated considering every rock mass layer and it depends almost linearly on the depth H.
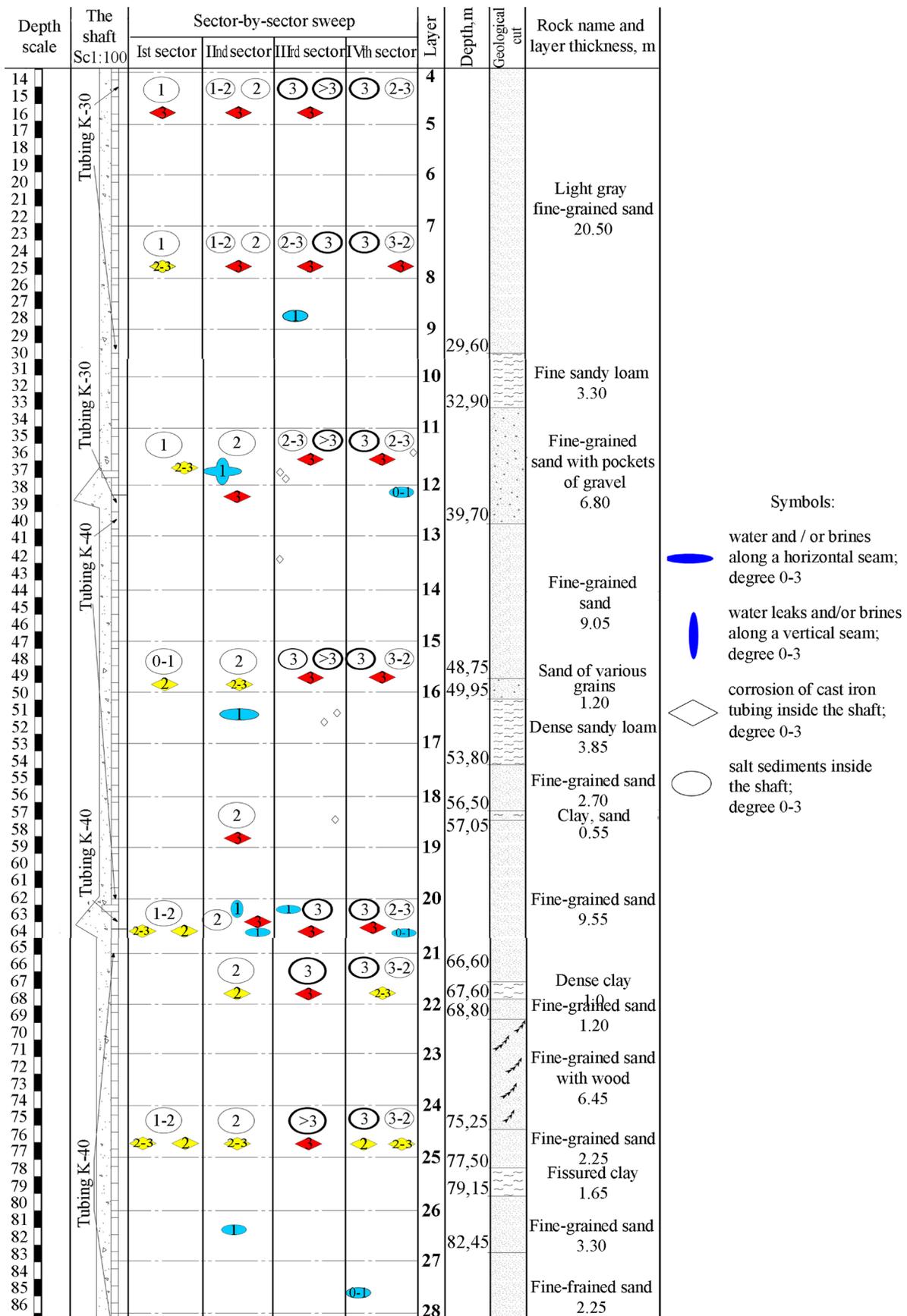
Fig. 1. Mining-geological and mining-technical conditions and technical condition of the lining
of shaft No. 1 of mine 3 on layers 4–28

With a known value of the external pressure on the vertical mine shaft, the stresses in the *i*-th cross section of the shaft can be calculated using the Lame formulas for a thick-walled cylinder [20]:

$$\sigma_{ri} = -\frac{1}{r_i^2 - r_{0i}^2}\left[p_{(1)i}r_i^2\left(1 - \frac{r_{0i}^2}{r_i^2}\right) + p_{(0)i}r_{0i}^2\left(\frac{r_i^2}{r_{0i}^2} - 1\right)\right]; \tag{1}$$

$$\sigma_{\tau i} = -\frac{1}{r_i^2 - r_{0i}^2}\left[p_{(1)i}r_i^2\left(1 + \frac{r_{0i}^2}{r_i^2}\right) - p_{(0)i}r_{0i}^2\left(\frac{r_i^2}{r_{0i}^2} + 1\right)\right], \tag{2}$$

where σ_{ri}, $\sigma_{\tau i}$ – the internal normal and shear stresses, Pa; r_i, r_{0i} – the project and the internal radii of shaft lining for the circle cross-section, m; $p_{(0)}$, $p_{(1)}$ – the internal and the external pressure correspondingly, Pa.

If the external pressure on the mine shaft is equal to the value at its bottom, and the internal pressure is equal to zero, equations (1), (2) take the form:

$$\sigma_{ri} = -\frac{1}{r_i^2 - r_{0i}^2}q_{bi}r_i^2\left(1 - \frac{r_{0i}^2}{r_i^2}\right); \tag{3}$$

$$\sigma_{\tau i} = -\frac{1}{r_i^2 - r_{0i}^2}q_{\text{н}i}r_i^2\left(1 + \frac{r_{0i}^2}{r_i^2}\right). \tag{4}$$

However, the obtained equations (3), (4) are valid for sections with only concrete lining of a constant cross section. In the remaining sections of the shafts, it is necessary to use formulas for compound cylinders. Their application is difficult due to the changing thickness of the tubing and the concrete ring around the tubing. At different depths the cross-sections of shaft No. 1 of mine 3 vary in external R_{external} and internal R_{internal} radii, the thickness of concrete t_{concrete} and cast iron $t_{\text{cast iron}}$ lining, as well as in the characteristics of the elements forming the annular section of the mine shaft (table).

Characteristics of the shaft No. 1 of mine 3 lining (H = 623.8 m)

H, m		Concrete lining				Cast-iron tuning		
from	to	R_{external}, m	R_{internal}, m	t_{concrete}, mm	Concrete type	R_{external}, m	R_{internal}, m	$t_{\text{cast iron}}$, mm
0	12.60	4.020	3.500	520	200	–	–	–
12.60	38.90	4.050	3.530	520	200	3.530	3.500	30
38.90	116.52	4.060	3.540	520	200	3.540	3.500	40
116.52	193.02	4.070	3.550	520	200	3.550	3.500	50
193.02	220.00	3.910	3.550	360	200	3.550	3.500	50
220.00	322.54	3.920	3.560	360	200	3.560	3.500	60
322.54	615.57	4.000	3.550	450	200	–	–	–
615.57	623.8	3.810	3.610	200	200	3.610	3.550	60

Typical defects of the cast-iron tubing and concrete lining of the shaft No. 1 of mine 3 are shown in fig. 3.

Therefore, there should be implemented the numerical approaches to solving problems on the mine shaft lining strength. So, the analysis of the stress-strained state of the shaft No. 1 of mine 3 is performed using the Static Structural component of the ANSYS Workbench. Computer simulations are performed for the design and 60 % values of tubing thicknesses in accordance with the results of the mine shaft control given in [18]. The stress-strain state of the shaft lining is analyzed at various values of the concrete lining thickness: from 100 to 60 %.

The following characteristics of the shaft lining materials are accepted [21; 22]: density: ρ_{concrete} = 2000 kg/m³; $\rho_{\text{cast iron}}$ = 7600 kg/m³; elasticity modulus: E_{concrete} = 23.5 MPa; $E_{\text{cast iron}}$ = = 83.4 · 10⁴ MPa; Poisson's ratio: μ_{concrete} = 0.2; $\mu_{\text{cast iron}}$ = 0.25. The parameters of the shaft
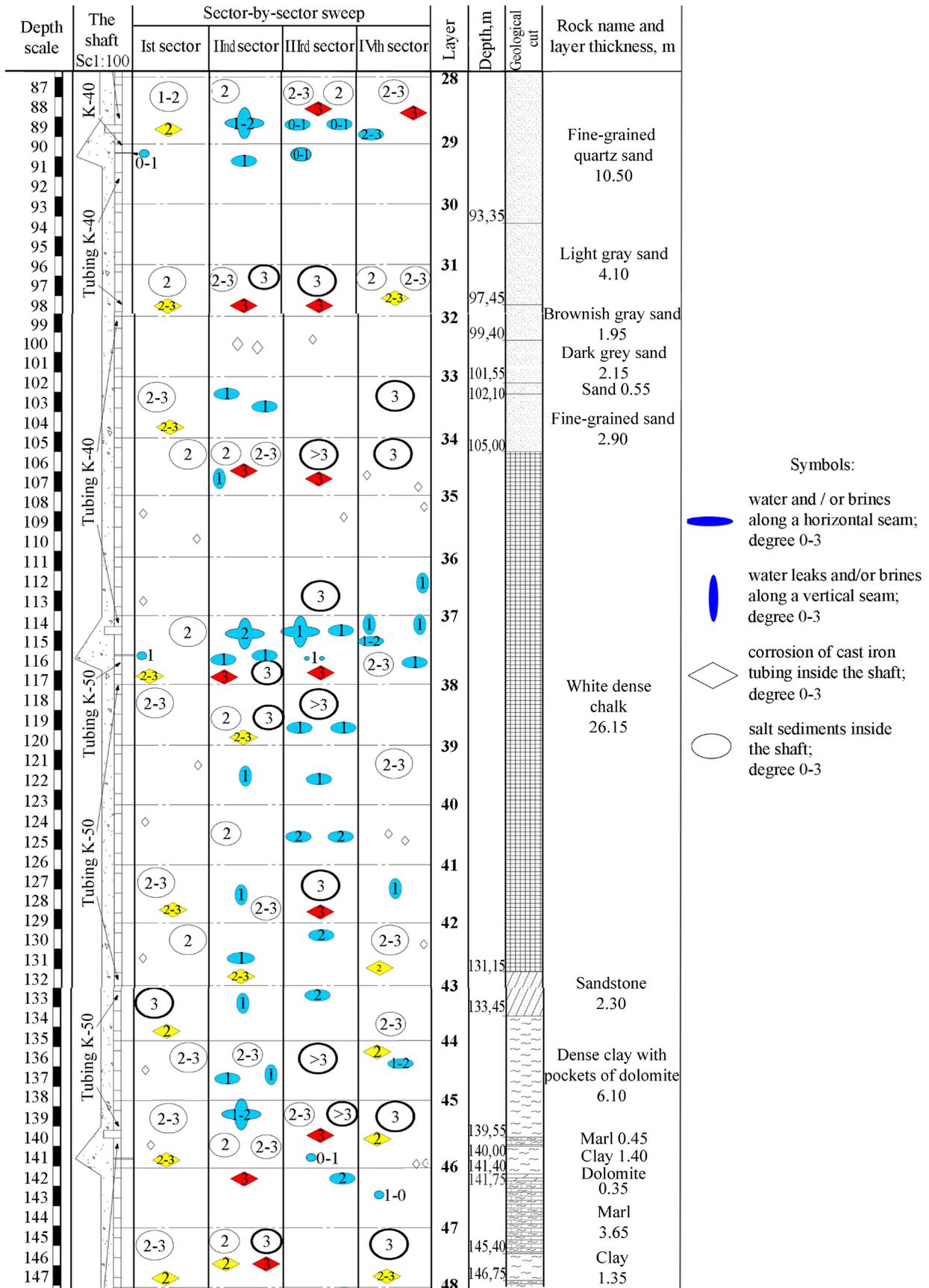
Fig. 2. Mining-geological and mining-technical conditions and technical condition of the lining of shaft No. 1 of mine 3 on layers 29–47
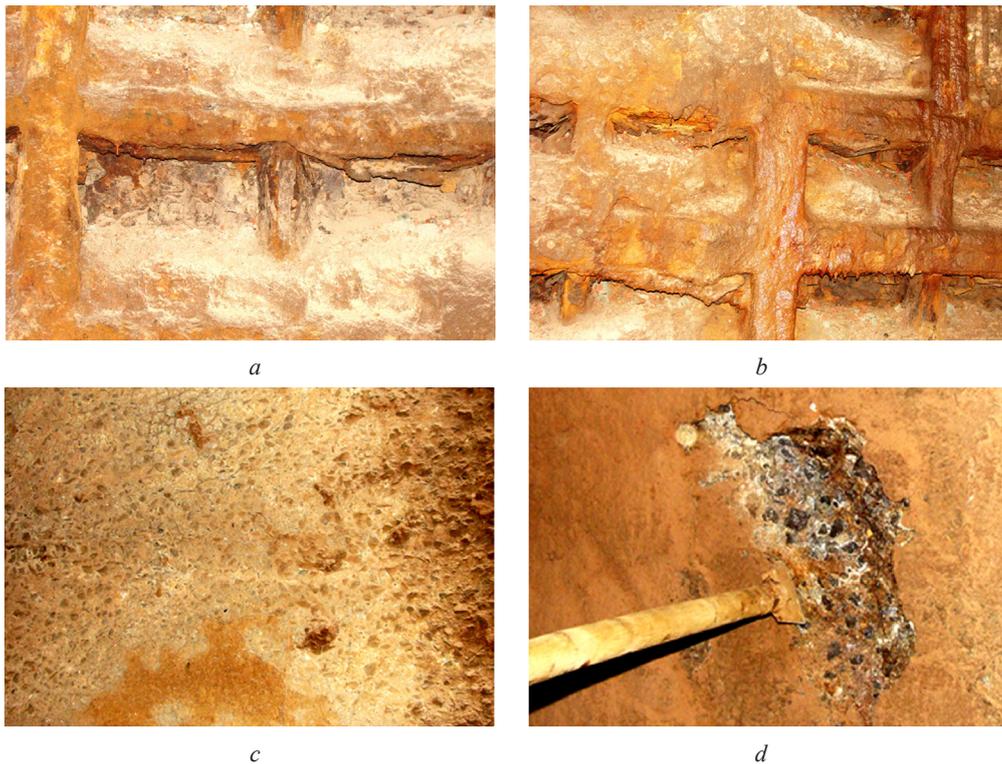
Fig. 3. Examples of the changed state of tubing and concrete lining of shaft No. 1 of mine 3:
a, *b* – defects of cast-iron tubing; *c*, *d* – the condition of the lining

loading are taken from the [19]. The geometry, finite element models and the loading scheme of the mine shaft on lauers 1–47 are shown in fig. 4. The lower part of the considered shaft section is fixed from vertical movements.

The peculiarity of the performed analysis is that it is a multibody analysis and there are the surface-to-surface contact areas between the cast-iron tubing and the concrete lining around the tubing. The convex tubing surface is chosen as a contact surface and concave concrete surface is chosen as a target surface.

Computer simulation results. The stress distribution diagrams in the longitudinal and lateral directions, as well as von Mises equivalent stresses in the cast-iron tubing of the vertical mine shaft were obtained for the cast-iron tubing and the concrete lining design and residual thicknesses values.

The computational results of the shaft stress-strain state demonstrate that when the cast-iron tubing thickness is thinned by 40 %, the maximal von Mises equivalent stresses reach 162.86 MPa and exceed the values obtained for the design structure of the considered part of the shaft by 60.28 %. The maximal compressive stresses in the longitudinal direction of the shaft increase by 118.07 %, and the shear stresses increase by 54.89 %, but they don't exceed the allowed values for the cast iron (fig. 5, *a*).

With the design geometry of the vertical shaft, the maximal normal stresses values in the concrete lining reach 7.830 MPa, the maximal shear stresses are 4.858 MPa.
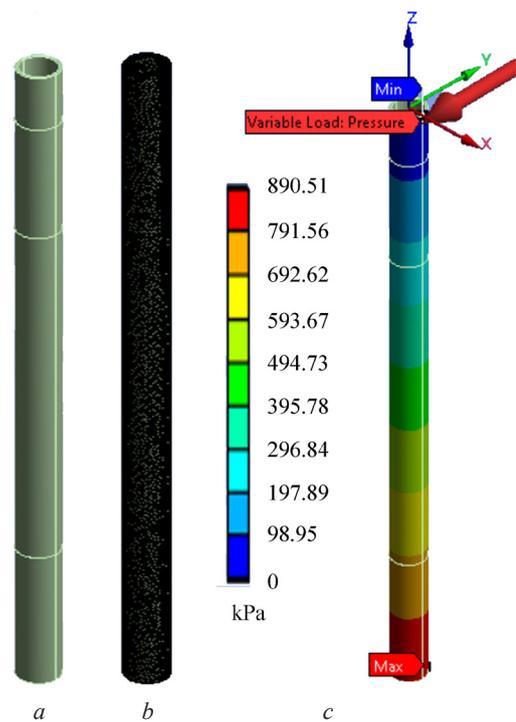

Fig. 4. The geometry, finite element models of the shaft No. 1 of mine 3 (layers 1–47) and the lateral loading scheme: *a* – geometry model; *b* – finite element model; *c* – lateral loading scheme
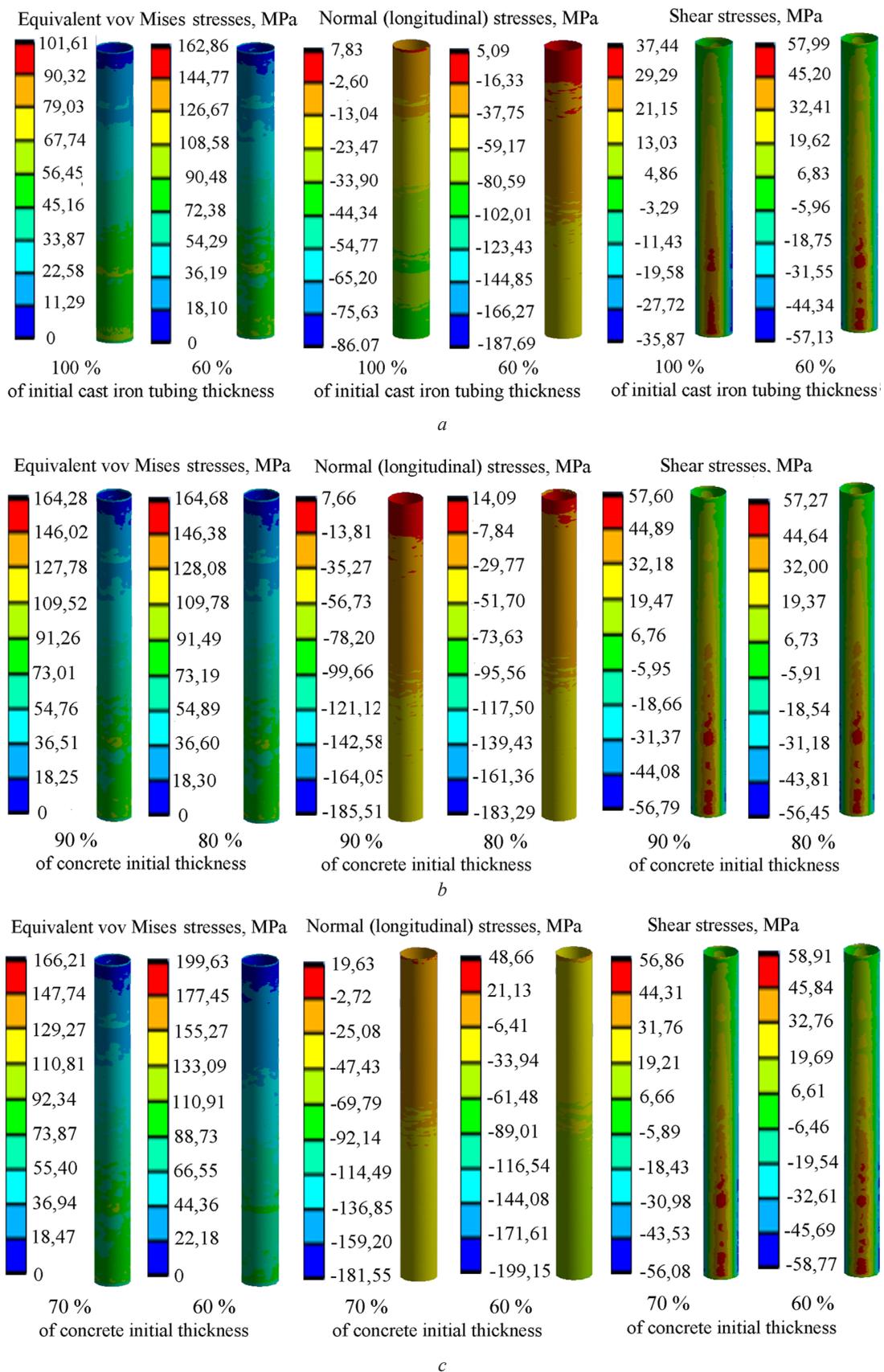
Fig. 5. The results of the stress-strain state calculation for the cast-iron tubing of the shaft No. 1 of mine 3 (layers 1–47):
a – at its initial and changed and thicknesses (at 100 % of the initial thickness of concrete);
b, *c* – with different thickness of concrete lining (at 60 % of the initial thickness of cast-iron tubing)

With a changed thickness of cast-iron tubing, the maximal values of normal stresses in the concrete lining reach 17.806 MPa, the maximal shear stresses values are 6.825 MPa.

For the projected thicknesses of the cast iron tubing and concrete lining the maximal deformations are 0.299 mm in longitudinal and 0.785 mm in lateral directions and 4.024 mm in longitudinal and 7.058 mm in lateral directions correspondingly. When the thickness of the cast-iron tubing is reduced to 60 %, the maximal deformations of the tubing are 0.300 mm in longitudinal and 0.797 mm in lateral directions; of the concrete lining: 4.091 mm in longitudinal and 7.091 mm in lateral directions.

Other results are obtained for various residual thicknesses of concrete lining and the 60 % thickness of cast-iron tubing (fig. 5, *b*, *c*).

The performed calculations show that at concrete thickness of 70–90 % from the initial value, the equivalent von Mises stresses increase insignificantly (up to 3 %) compared to the results obtained for the initial concrete thickness in the space around cast iron tubing.

When the concrete thickness reaches 312 mm (it is 60 % of the initial thickness of the concrete lining) there can be observed a sharp increase in the maximal equivalent stresses by 21.22 %. In this case, the maximal deformation of the tubing is 0.375 mm in longitudinal direction and 0.796 mm in lateral direction; in the concrete lining: 4.105 mm in the longitudinal and 7.091 mm in the transverse directions; the maximal normal stresses in concrete in the longitudinal direction of the shaft are 21.125 MPa, the maximal shear stresses reach 6.964 MPa.

Conclusions. For the analyzed part of the lining (layers 1–47) shaft No. 1 of mine 3, at the most unfavorable conditions (residual thicknesses of the cast iron tubing and behind-tubing concrete lining), the maximal equivalent von Mises stresses reach 199.63 MPa and they are 96.47 % higher than the values obtained for the initial thicknesses of the considered shaft part cross-sections. The maximal longitudinal compressive stresses increase in this case by 131.38 % for the cast iron tubing and by 169.80 % for the concrete lining.

Normal stresses in the shaft concrete lining increase by 19 % and more with a decrease in its thickness by 30 % and more for the case of 60 % cast iron tubing thickness. Additionally, it is necessary to take into account the factor of deterioration of concrete properties over a long period of the mine operation.

It is recommended to carry out regular diagnostics of the cast-iron tubing and concrete lining state, as well as to implement measures to strengthen the cast-iron tubing and restore the bearing capacity of the mine shaft to reduce the likelihood of an emergency during its operation.

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