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Analysis of shaft lining stress state in anhydrite-rock salt transition zone

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Abstract

The main question of this paper is the stress-strain state prediction of the vertical shaft's combined lining located at the interface of two layers of dolomite and salt. The study predicts geomechanical processes at the contact of the dolomite layer and the salt layer in the vicinity of the vertical shaft's expanded section, taking into account the operating life of a vertical shaft is equal to 50 years. The results combined lining's stress-strain state, represented as a four – layer medium, where the external layer is concrete, and the three inner layers are used to account for the heterogeneity of cast-iron tubing and are compared with the results received when taking into account the pipe structure. The solution of the problem was carried out in a three-dimensional statement. The calculation of the tubing lining, considering its actual geometry, will increase the accuracy of the forecast of the stress state of the lining, which in turn will favourably affect the justification of its parameters.

Keywords:
lining; salt rock; load; state of stress; transitional area; rheology; tubing

1. Introduction

The construction of vertical shafts in salt mines at great depths is associated with intensive geomechanical processes, which introduce uncertainty in the choice of lining type and justification of its parameters, and also have a significant impact on the long-term stability of the shafts and the technical condition of the lining. The vertical shaft's lining stresses forecasting of and the prediction of the vertical shaft's lining stress state in salt massifs have received considerable attention from researchers. As a result of the evolution of rheological processes in the salt rock massif, the displacement of the contour (**Kamiński, P., & Czaja, P., 2019**) of vertical shafts is intensified both during construction and operation, which manifests itself in the form of an ever-increasing load on the lining of the shaft. As noted by the researchers, even at depths of 350-400 m from the surface of the ground, the stress state of the lining of shaft located in salt soil body can reach the strength limit of the lining material, and the lining itself can be damaged (**Kazikaev D.M. & Sergeev S. V., 2011**). Although such damage in most cases is confined to the junctions of the vertical shaft with the horizontal mine workings, in some cases such damage is also noted on the expanded section of the shaft. With an increase in the depth of deposit development, the depth of the vertical shaft is also increased, and, accordingly, the load on the lining increases, which leads to an increase in the number of areas where the lining is damaged or partially destroyed (**Kazikaev D.M. & Sergeev S. V., 2011; V.A. Solovyov et al., 2017**). Thus, the requirements for the reliability of methods for forecasting the lining's stress state and predicting the development of geomechanical processes in the rock massifs are increased. Particular focus should be given to the sections where the vertical shaft route crosses from solid rock to salt strata, the formation of the stress state in the shaft lining, on which little attention is paid in scientific publications, and the choice of lining parameters is not obvious.

At present, design methods of loads on lining and stress state of mine lining have been developed based on different hypotheses of rock pressure formation, which have been realized within the framework of theories of structural mechanics and continuum mechanics, and a number of experimental and analytical methods (**Bulychev N. S., Abramson H. I., 1978; Kazikaev D.M. & Sergeev S. V., 2011**). Among the methods for calculating the stress state of supports and linings, one can distinguish the method proposed by N. S. Bulychev (**Bulychev, N.S. et al., 1982; Stras, J. 1986; Kazikaev D.M. & Sergeev S. V., 2011; Hentrich et al., 2019**), who, within the framework of the scheme of joint interaction, obtained an analytical solution for the formation of loads on the support of a circular mine located in an isotropic

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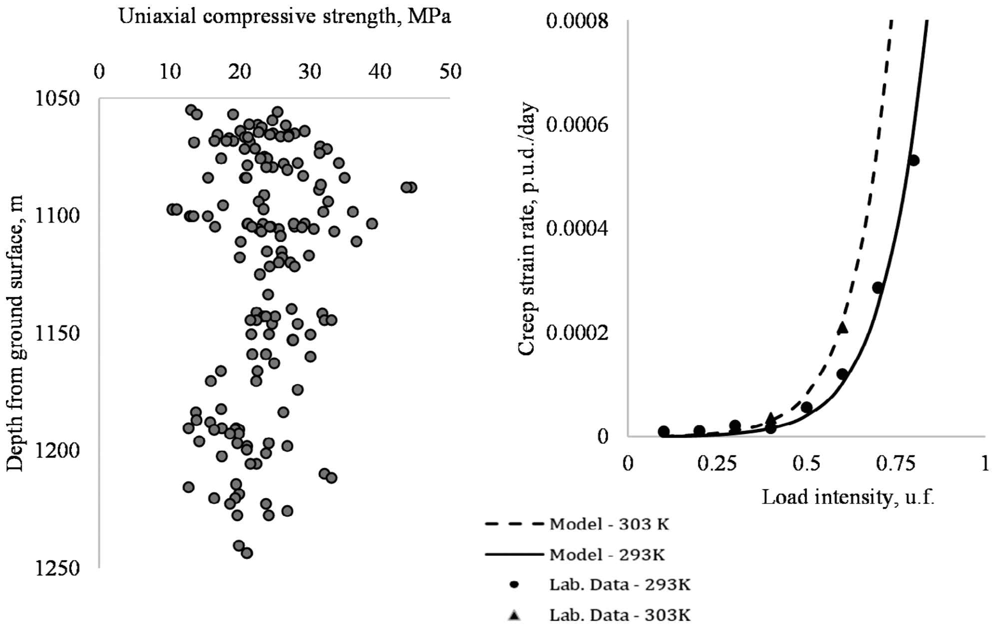
linear-deformable medium. However, this solution is limited to plane deformation conditions and cannot be extended to areas requiring a spatial representation of the problem. A second significant disadvantage is the treatment of the tubing lining as a multi-layer ring (MRL), which imposes some constraints on the determination of the local area stresses of the lining.

The application of numerical methods of analysis allows for the possibility to avoid a number of assumptions and simplifications presented in analytical solutions and enhance the reliability of solving the problem of predicting the vertical shaft lining deflection. There have been many studies on these issues. For example, the authors (**Konstantinova, S. A., Chernopazov, S. A., 2006**) give an example of calculating the shaft support loads using the finite element method. (**Jia Yudan, 2010; Jia, Y. D. et al., 2013**) discussed the method of calculating vertical shaft lining by means of numerical modelling. Also, in their work, they described a study where the stress state of a concrete lining of a vertical shaft located in salt formations was predicted by taking into account the time factor. In a study carried out in (**G. T. Du Judeel et al., 2011**), the stress-strain state of a vertical shaft lining located in a salt massif, taking into account rheology, was predicted on the basis of mathematical modelling. In (**G. T. Du Judeel et al., 2012**) an approach to the prediction of loads on a vertical shaft tubing lining in a flat setting, in which the tubing lining is considered in a longitudinal section reflecting the geometry of the tubing lining stiffening ribs, is presented. This approach made it possible to identify areas of maximum stress concentration and, based on this prediction, recommendations were made for the selection of parameters for tubing lining located in different rock layers along the shaft route. The author (**Slawomir Bock, 2014**) has carried out a study related to numerical modelling of the occurrence of voids in the backfill space of vertical shaft lining in a layered massif. In (**Fabich, S. et al., 2015**) the stress state of the temporary and permanent support of the deep vertical shaft of the Victoria Mine was investigated based on numerical modelling. In (**Ozturk, H., Guler, E., 2016**), a method of determining the parameters of vertical shaft lining, based on the prediction of the stress state around the shaft, was proposed. In a study (**Georgiannou, V. N., 2017**), loads on a prefabricated vertical shaft lining were calculated for both planar and volumetric conditions. In (**V.A. Solovyov et al., 2017**) a method of prediction of stress state of vertical shaft lining considering rheological properties of rock salt on the example of Verkhnekamskoe deposit is presented. In (**Tiutkin et al., 2019**) a volumetric problem is considered, within the framework of which modelling of concrete and cast-iron tubing lining of a shallow vertical shaft located in an irregularly thawing ice massif is carried out. Tubing is presented as a single-layer elastic medium. This paper (**He, Xiaonan et al., 2019**) considers the calculation of a monolithic concrete lining of a deep vertical shaft, and compares it with the load calculations obtained by numerical modelling). This paper (**Jendryś, M., 2019**) presents a numerical method for calculating vertical shaft lining, taking into account the integrity of the lining. The paper (**M. A. Karasev et al., 2019**) deals with prediction of stress state of a section of combined lining of vertical shafts of 6.0 and 7.0 m diameter located in salt formations. The combination shoring consists of a concrete layer and a cast-iron tubing lining. Cast-iron tubing lining is regarded as a two-layer system, with each layer having a different stiffness. This approach was proposed by N. S. Bulychev for the calculation of multi-layer lining. As the author of the methodology notes, the results of the load calculation for the shoring compare well with the results of in-situ observations. The authors (**Sun, X. et al., 2019**) consider a deep vertical shaft lining at the contact of two rock layers. This paper (**Sun Q. et al., 2020**) presents a prediction of the loads and displacements of the rock contour of an extended section of vertical shaft. The authors (**Naseri, S., Bahrani N., 2021**) considered the numerical simulation of vertical shaft lining shotcreting in a flat setting.

Thus, as can be seen from the analysis of scientific publications at the present stage of development of mechanics of underground structures, the main direction of increasing the reliability of prediction of the deflected stress state of the "lining - rock mass" system is to improve numerical models for forecasting the stress state, as well as to solve this class of problems in the spatial formulation. In this paper, we propose a methodology for predicting the stress state of the vertical shaft lining, located at the contact of two rock layers - dolomite and rock salt. The innovation of this methodology is in the consideration of cross-sections, taking into account the detailed geometric configuration of the cast iron tubing lining in order to increase the reliability of the prediction of stress development within the structure. The problem was solved considering the rheological properties of the salt massif, in the temporal formulation. The results of the stress state of the vertical shaft lining are compared in the spatial idealization of the shaft lining and in its consideration as a multilayered medium. These studies were carried out as part of the design and calculation of shaft lining in the Nivenskoe deposit. The proposed study can be used for further implementation of the methodology for calculating parameters of shaft lining of the Nivenskoe deposit.

1.1. General information about the object of study

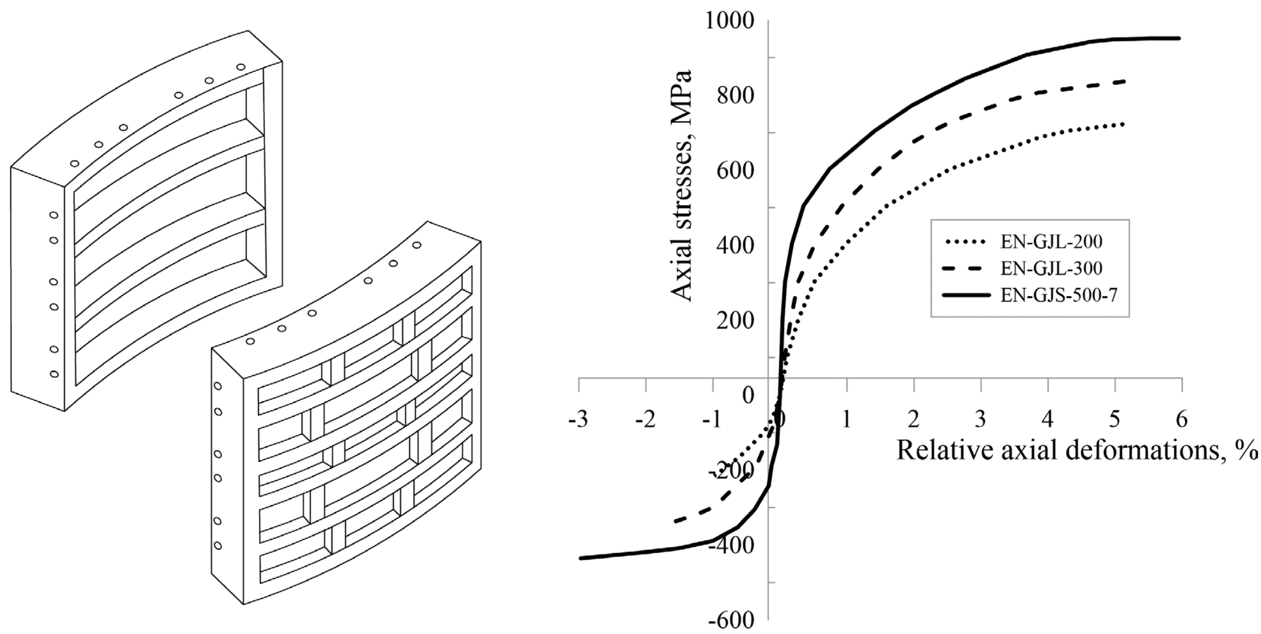
Conventionally, the geotechnical conditions along the route of vertical shafts, when developing deep salt deposits (1000 m or more in depth), can be divided into 4 zones: Zone I - sandy and clayey rocks, predominantly waterlogged, characterized by low mechanical characteristics, unstable; Zone II - argillite-like clay rocks,



(a) Variability of strength properties of salt rocks

(b) characteristic dependences of creep rate change on loading intensity and temperature

Figure 1: Mechanical characteristics of salt rocks



(a) Structural solution of tubing lining

(b) features of mechanical behaviour of different grades of cast iron under different types of stress state

Figure 2: Cast iron tubing characteristics

characterized by low mechanical characteristics, prone to significant deformation, unstable at the depths in question; Zone III - hard rocks composed of limestone, anhydrite and dolomite, stable; Zone IV - salt rocks prone to rheological processes, relatively stable. The present study focuses on the mining and geomechanical conditions of the transition area between Zone III (composed of anhydrites, marls and dolomites) and Zone IV (rock salt of different mineralogical composition).

The rocks that belong to the third zone have considerable strength reserves for the conditions in question, and their propensity to develop rheological processes is very low. The main mechanism for the loss of stability of such rocks in the near-surface zone is quasi-static failure of rocks with their subsequent collapse into the mined-out space. However, this process is only characteristic when the rock contour is exposed for a long period of time without the installation of fasteners, which generally does not correspond to the technological features of vertical shaft construction. The rock deformations are linear and less likely to change to an elastic-plastic deformation, given the introduction of the lining immediately after the face advances and the significant resistance of the lining to the deformations of the rock contour. Thus, the use of simple elastic or elastoplastic models is sufficient to predict the development of geomechanical processes in rocks belonging to zone III.

In contrast, salt rocks (zone IV rocks) are geomaterials that deform actively over time, especially under rock stresses comparable to the ultimate strength of salts in uniaxial compression. The uniaxial compressive strength of the rock varies between 20 and 30 MPa (see **Figure 1a**), although individual samples may have lower or higher strengths, with initial stresses of up to 25 MPa in the salt rock. The rate of creep deformation (see **Figure 1b**) as the stress intensity (ratio of effective stresses to rock strength in uniaxial compression) increases significantly, which affects both the reduction in the duration of stable mine workings and, in the case of a vertical shaft, the magnitude of the load on the buttress. The salt rock massif is a viscoplastic medium whose long-term deformation development is determined by the salt stress condition formed as a result of construction and subsequent operation.

In terms of mining conditions, a vertical shaft with an internal diameter of 7.0 m and an external diameter of 9.0 m is considered to be constructed using a mechanized shaft sinking system. As shaft lining in zone III can be considered concrete, reinforced concrete, steel-concrete and cast-iron tubing lining can be considered, and in some cases (when substantiating the corresponding technological scheme of shaft operation) without any lining at all. Experience (**Kazikaev D.M., Sergeev S.V., 2011; V.A. Solovyov et al., 2017**) shows that the use of concrete and reinforced concrete lining cannot ensure the long-term stability of a vertical shaft at great depths in salt formations. This means that either lightweight lining structures (flexible or rigid anchors, with parameters justified for the design life of the shafts) are used to line the shaft, or a cast-iron tubing lining structure with sufficient load-carrying capacity to bear external loads is used as a lining. This work considers the option of securing rocks in Zone III and Zone IV with cast-iron tubing lining.

The load-bearing capacity of a tubing lining is characterized by two parameters, the geometric dimensions of the tubing (see **Figure 2a**) and the mechanical characteristics of the cast iron (see **Figure 2b**).

Thus, the transition area between Zone III and Zone IV is characterized by considerable variability in both the mechanical behaviour of rocks and the intensity of geomechanical processes at the contour of the vertical shaft. It is expected that the shaft lining at the transition section is deformed not only by the transmission of radial loads, but also by its bending along the length of the shaft. Thus, the approach based on performing calculations of the shaft lining under conditions of flat deformation is not reliable, and to calculate the lining in this area, it is necessary to build a spatial model that explicitly takes into account the geometric features of the tubing lining.

2. Lining design method

2.1. Numerical model of "lining-rock" interaction system

When performing numerical simulations, the reliability of the calculations depends on the various parameters of the numerical model, among which the choice of a deformation model for the geomaterials and lining materials should be the main focus. As noted above, the work considers the construction of a vertical shaft in a transition zone, at the boundary between a layer of hard rock (anhydrite, dolomite) and the salt layer. The fastening material considered is high-strength cast iron with the backfill space filled with concrete.

Anhydrides in the calculations are idealized in the form of an elastic-plastic medium based on the Coulomb-More plasticity condition (**Labuz, J. F., Zang, A., 2012**). In the classical form, the Coulomb-More plasticity condition can be written in the form of the equation:

$$\tau_{\text{пр}} = c + \sigma_n \text{tg}\varphi, \tag{1}$$

Where:

$\tau_{\pi p}$ is the shear strength at the considered site;

σ_n is the normal stress acting perpendicular to the considered site;

c – cohesion;

φ –angle of internal friction.

To describe the mechanical behaviour of the salt layer, a viscoplastic model based on the power law of creep (**Van Sambeek L.L. 1986**) is adopted. This model allows a description of the first stage of creep (primary creep) and partly the second stage of creep (steady-state creep). In view of the fact that the work considers the process of development of long-term deformation of the salt strata, taking into account the repulsion of rigid lining and cast-iron tubing, the third stage of creep (progressive creep) is not expected and may occur only in the contour zone of the shaft. Thus, the proposed model has sufficient functionality to solve the set problem. The relationship between creep increment and rock state is presented in analytical form:

$$\dot{\varepsilon}^{cr} = \left(Aq^n \left((m+1)\varepsilon_{cr} \right)^m \right)^{\frac{1}{m+1}} \tag{2}$$

Where:

A, m, n are model indices;

$\overline{\sigma}_{cr}$ – equivalent creep stresses;

$\overline{\varepsilon}_{cr}$ – equivalent relative creep strains.

The model has shown good agreement with the results of in-situ observations (see **Figure 7**).

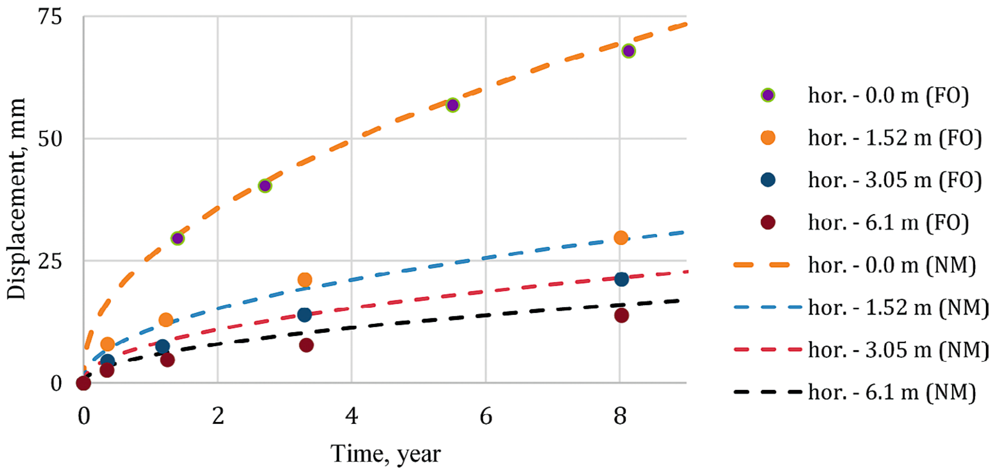


Figure 3: inverse calculation of the rheological parameters of the model. Where "FO" - field observation; "NM" – numerical modelling.

Table 1: Averaged mechanical characteristics of zones III and IV

№ p/p	Parameter	Unit of measurement	Average values of the mechanical characteristics of the rocks	
			III zone	IV zone
1	Deformation modulus	MPa	50 0000	20 000
2	Transverse strain factor	-	0.30	0.35
3	Rock strength in uniaxial compression	MPa	50	25
4	Cohesion	MPa	15	3
5	Angle of internal friction	grad.	45	35

In view of the considerable variability in the properties of Zones III and IV, the average elastic and plastic properties of these rocks have been assumed in the numerical modelling (see **Table 1**). These parameters were obtained from laboratory tests conducted at the Saint-Petersburg Mining University in 2020. For salt rocks, the creep parameters are as follows: $q_0 = 250$ MPa/day, $n = 3$, $m = -0.43$, $\varepsilon_0 = 1$. The rheological parameters of the long-term salt deformation model are selected on the basis of an inverse calculation. An excavation (**Dawson, P. R., Munson, D. E., 1983**) located in the salt stratum at a depth of 1000 m from the ground surface is considered as an object for the inverse calculation (see **Figure 3**).

The behaviour of cast iron and concrete was considered within the framework of elasticity theory. It is assumed that the deformation modulus of concrete is 30 GPa, with a Poisson's ratio of 0.2. The calculations take into account the reduced deformation properties of the concrete due to the particular long-term deformation characteristics of the concrete.

The cast-iron tubing lining is made of cast-iron grade EN-GJS-700-2. The modulus of elasticity of this iron grade is 180 GPa and the Poisson's ratio is 0.2. Considering that in the vertical shaft section under consideration the stress state of the tubing is considerable and stresses may exceed the elastic limit of cast iron, the elastic-plastic model, Cast Iron Plasticity, is additionally adopted to describe the mechanical behaviour of cast iron. The model has proven itself well suited to describing the behaviour of materials which behave differently under compressive and tensile conditions. In the area of compressive stress, the surface of the plastic flow is described by the Mises condition, whereas in the area of tensile stresses, the following condition is adopted:

$$F_t := R_r(\Theta)q - p - \sigma_t = 0$$

$$F_c := q - \sigma_c = 0$$

$$R_r(\Theta) = \frac{2}{3}\cos\Theta \qquad (3)$$

Where:

σ_t – is the strength of cast iron under uniaxial tension;
σ_c is the strength of cast iron under uniaxial tension;
q is the intensity of normal stresses;
p is the average stress;
Θ is the Lode angle.

The model parameters $\boldsymbol{\sigma_c}$ and $\boldsymbol{\sigma_t}$ are functions of plastic strain increments.

2.2. *Design of cast-iron lining*

The work considers the prediction of the stress state of a vertical shaft at 1000 m from the ground surface (see **Figure 4**). In the rock massif, a 150m long section

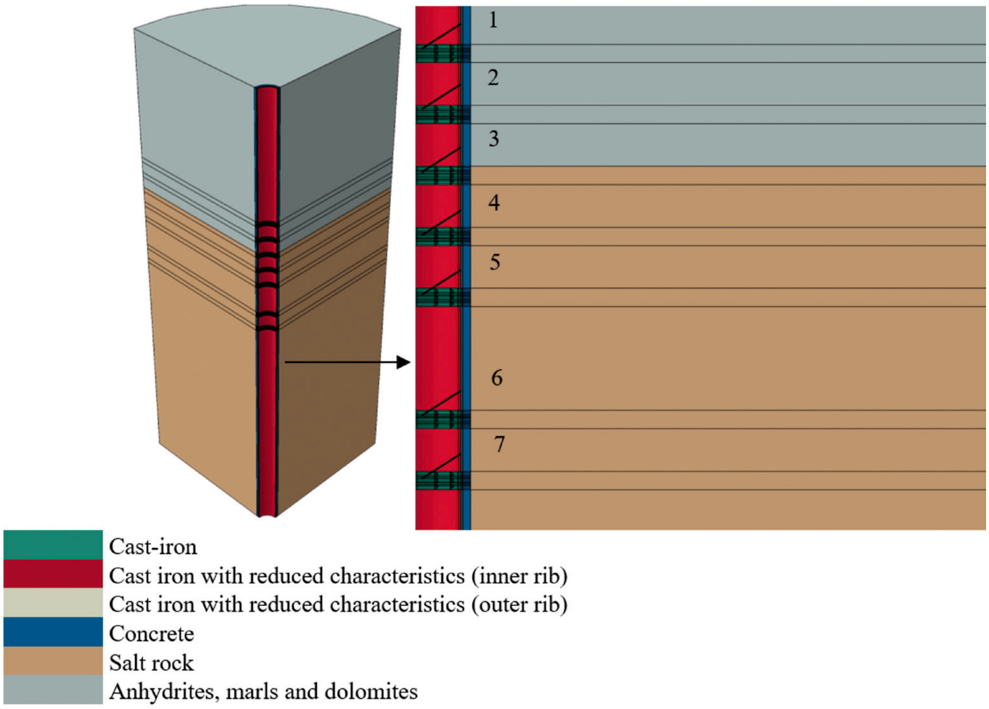


Figure 4: Diagram of the location of stress measurement sections along the shaft route in the support: 1-7 - positions of the sections where the stress state of the lining was measured.

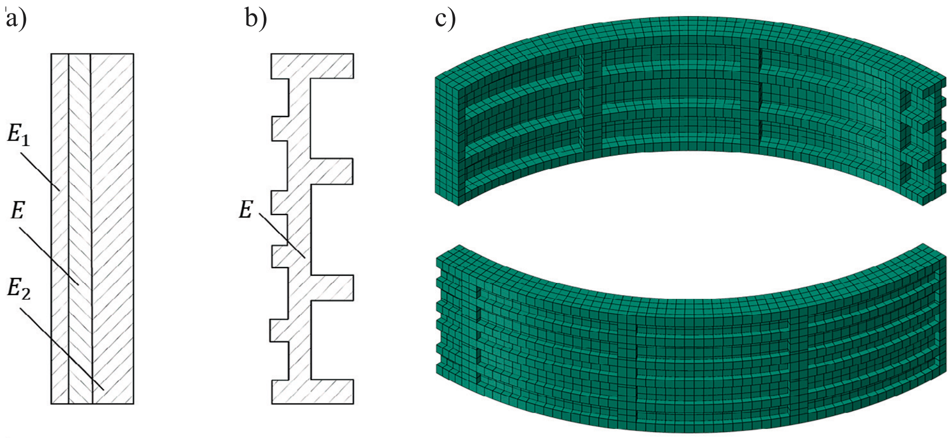


Figure 5: Modelling of the tubing lining. a) computational representation of the tubing lining as a multilayer structure, where E is modulus of elasticity of the backrest material, E_1 is modulus of elasticity of outer ribs, E_2 is modulus of elasticity of the inner ribs; b) computational representation of the tubing lining in the axisymmetric setting; c) computational representation of the tubing lining in the spatial setting.

is identified, located at the contact of two media, a 50 m thick solid mass and a 100 m thick salt mass. The vertical shaft, 9 m in diameter and 7 m internal diameter, is secured by a combined lining with a total thickness equal to 1 m. The shaft has 7 sections along its route, where the stress state of the lining was measured. In the solid rock strata, there are two stress measurement sections, 5 and 10 m distant from the transition section. In the salt strata, there are four stress measurement sections at distances of 5, 10, 20 and 25 m from the contact between the solid rock and the salt.

The vertical shaft tubing lining is a three-layer structure that includes inner ribs, back and outer ribs. To calculate the stress state of such a lining, the method proposed by N. S. Bulychev (**Bulychev N. S., Abramson H. I., 1978**) is traditionally used, according to which the real structure of a tubing lining is replaced by a multilayer ring, where each layer is responsible for the work of the back or ribs. The fact that each layer has different mechanical characteristics makes it possible to achieve the same stiffness as a tubing lining. Thus, the deformation characteristics of the backbone are assumed to be

Table 2: Mechanical characteristics of the tubing support presented in the form of a multi-layer structure

Tube size	r_1, m	r_2, m	r_3, m	Modulus of elasticity of the backrest material E, MPa	Modulus of elasticity of the inner ribs E2, MPa	Modulus of elasticity of outer ribs E1, MPa	Yield strength, MPa
7.0-100	3.68	3.78	3.85	180000	52200	85292.31	420

Table 3: Plastic characteristics of cast iron grade EN-GJS-700-2

Mechanical behaviour in uniaxial compression		Mechanical behaviour in uniaxial tension	
Strain, MPa	**Equivalent plastic strains, d.e.**	**Strain, MPa**	**Equivalent plastic strains, d.e..**
200.0	0.000	129.5	0.000
297.0	0.001	184.3	0.001
397.3	0.002	237.3	0.002
495.9	0.004	299.1	0.004
591.7	0.007	345.9	0.006
691.0	0.014	381.8	0.010
757.1	0.020	400.6	0.015
791.0	0.023	411.1	0.020
828.7	0.028	427.3	0.030
890.6	0.037	447.8	0.037
924.9	0.046	468.2	0.040
931.0	0.050	494.6	0.043
933.6	0.055	-	-
933.6	0.060	-	-

equal to the mechanical characteristics of cast iron, while to determine the deformation characteristics of the ribs, it is necessary to lower the material deformation modulus of the ribs taking into account their actual area over the height of the tube (reinforcement factor) and numerically equal to the ratio of the sum of the stiffening rib thickness to the height of the tubing (see **Figure 5a**). However, this approach is not without disadvantages and proof of the validity of its use for the specific conditions of the lining loading is required.

When predicting the stress state of a shaft support located in an isotropic homogeneous medium, to obtain a reliable idea of the stress state of the shaft lining it is sufficient, from a geometrical point of view, to represent the lining in axisymmetric formulation as a set of finite elements repeating the cross-section of the tubing along its height (see **Figure 5b**). However, if the load on the lining varies considerably in the height of the shaft lining, as in the case of the transition section, the longitudinal ribs of the tubing, which are absent in the axisymmetric setting, may have a significant influence on the formation of the stress state of the lining. Thus, in the numerical simulation, the tubing lining is represented as a spatial structure (see **Figure 5c**) and the problem is solved in spatial formulation. In addition, calculations are made for a comparative analysis when the lining is presented as a multi-layer structure.

The design parameters for each layer of the tubing lining are summarized in **Table 2**. The plastic characteristics of cast iron are summarized in **Table 3**.

The modulus of deformation of layers with stiffening ribs is underestimated by introducing a coefficient equal to the ratio of the sum of the stiffener thicknesses to the tube height:

$$E_i := E \cdot k_0 \quad (4)$$

where:

E – is the Modulus of elasticity of the backrest material;

k_0 is the coefficient of the ratio of the sum of the stiffening ribs thickness to the tube height.

Finite-element models for forecasting the stress state of a tubing lining are shown in **Figure 6a** for multilayer lining and **Figure 6b** for spatial representation of tubing lining. The problems were solved under the following boundary conditions. The displacements along the lower and lateral boundaries of the model are forbidden in the direction orthogonal to these surfaces. A stress equal to 24.8 MPa is applied to the upper boundary of the model. The stress distribution in the salt layer is assumed to be hydrostatic, while the lateral pressure coefficient in the solid layer is assumed to be 0.6. To reduce the dimensionality of numerical models, only one quarter of the model was considered. The temperature of the rock mass was assumed to be 303 K, detailed representation of the tubing.

Numerical modeling was performed in the Abaqus CAE software package, and the calculation was carried out in three stages. At the first stage, the formation of the initial stress field of the rock massif was modelled. At

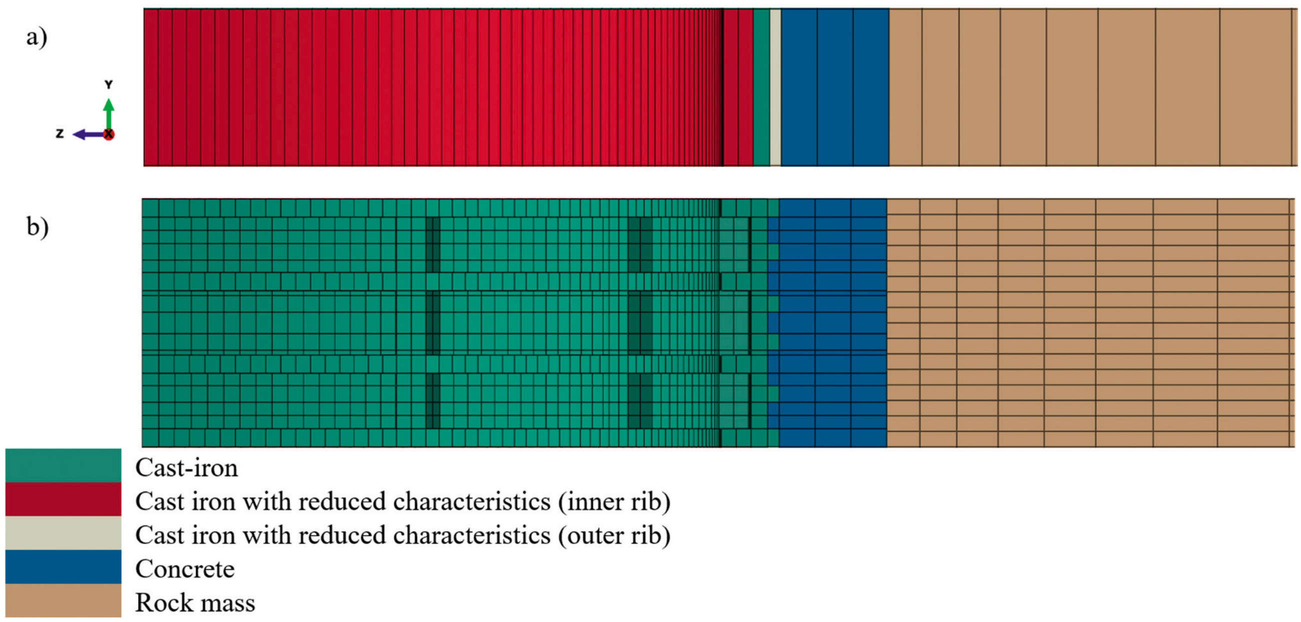


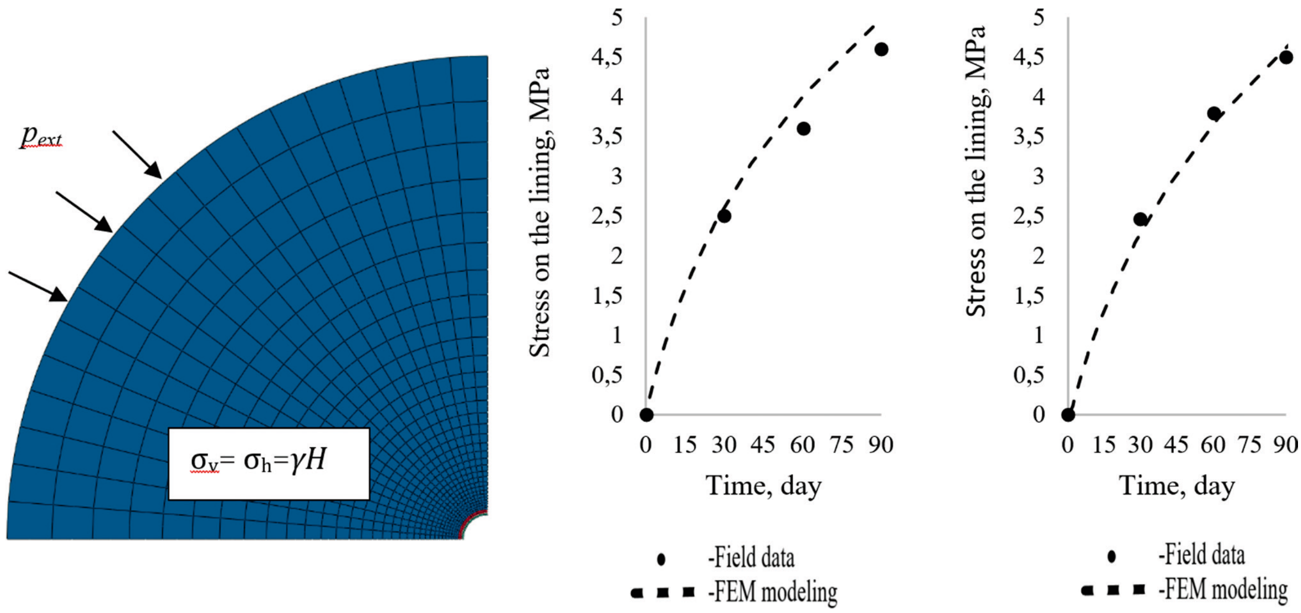
Figure 6: Finite-element models of the "lining - rock mass" system: a – multilayer structure; b – 3D structure.

the second stage, we modelled the change in the stress state of the rock mass, taking into account the peculiarities of the shaft construction technology and the lag of the fastener installation from the face of the face. At the third stage, we modelled the change in the "lining-rock massif" stress during a long period of operation equal to 50 years.

Numerical modelling was carried out in a non-stationary formulation, with a design time period of 50 years for the shaft lining.

3. Results

In order to assess the reliability of the proposed methodology, the results of the prediction of the vertical shaft lining and the data of instrumental measurements were compared. The proposed approach was tested by calculating the stress state of shaft lining at two mines, the Zakarpatsky Mine and the Piilo Mine. Detailed information on modelling is presented in (**M. A. Karasev et al., 2019**). As can be seen from the dependencies presented

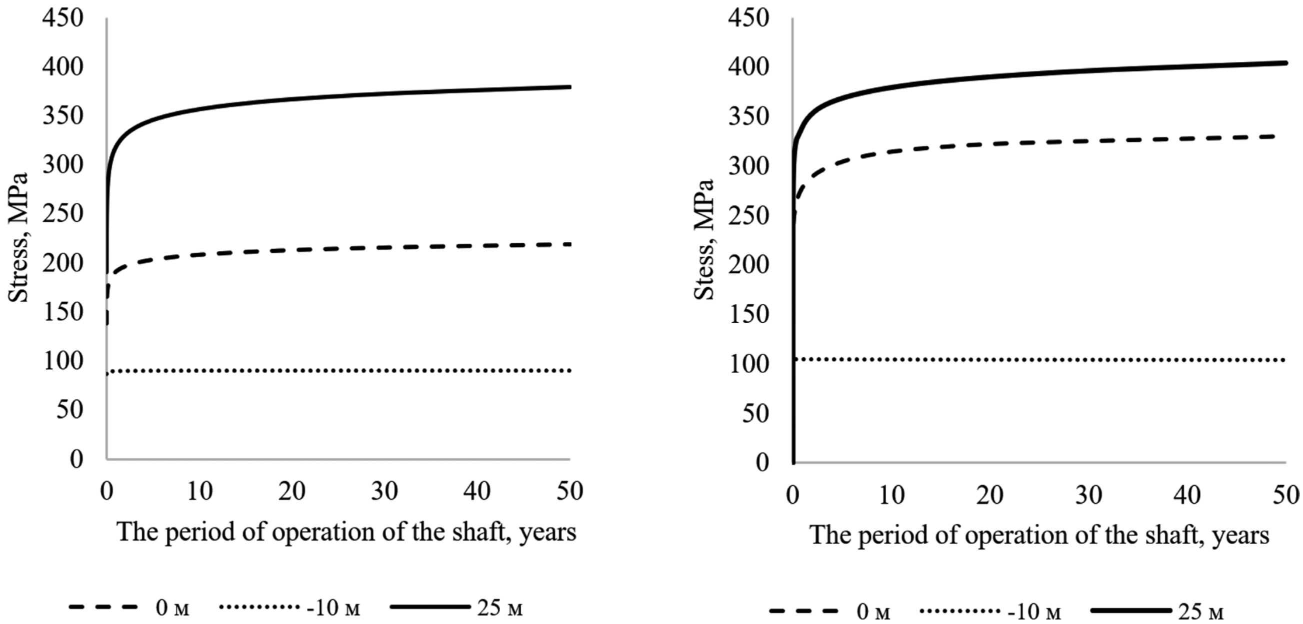


(a) calculation scheme

(b) in the shaft №9 of Zakarpattia salt mine at the depth of 492 m

(c) in the shaft of Piilo Mine at a depth of 491 m

Figure 7: Stress-strain prediction model for vertical shaft lining development of radial stress at the contact "lining - rock mass".



(a) with idealized tubing lining as MLR;

(b) with spatial representation of tubing lining.

Figure 8: Stress state of the tubing lining at the transition section

(see **Figure 7**), there is a good convergence between the results of in-situ observations and numerical modelling. Thus, it can be concluded that the proposed methodology gives satisfactory agreement with the actual stress state of the lining both from a qualitative and quantitative point of view.

On the basis of the performed calculations, the stress-strain state of the support of the vertical shaft is established. Characteristic patterns of the formation of the stress-strain state lining were obtained for the three considered sites located in solid rocks, at the contact of the salt column and solid rocks, as well as in the salt massif. The prediction of the stress state of the lining at the transition section of the vertical shaft is presented in the form of stress distribution diagrams (main maximum and main minimum normal stresses) as well as in the form of stress change relationships along the length of the vertical shaft.

Consider the formation of the stress state of a vertical shaft lining presented as a multi-layer structure (see **Figure 8a**). The maximum 50-year stresses for a dolomitic layer support at a distance of 5 m from the salt rock contact are in the order of 105 MPa, and at a distance of 10 m about 90 MPa. The maximum stresses in the lining at the contact with the salt massif are 220 MPa. The highest values of stresses in the lining for the extended section located in the salt massif are fixed at a distance of 20-25m and are about 375 MPa.

The distribution of stresses in a tubing shaft lining when it is idealized as a spatial structure gives an indication of the effect of changes in lining stiffness along its perimeter on the stress state (see **Figure 9**). During the calculations, an elastic model of the behaviour of the cast-iron lining was used in a first approximation, and this iteration resulted in the stresses in the lining exceeding the elastic limit of cast-iron. Thus, the maximum stresses in the lining were about 475 MPa (see **Figure 10a**) with a yield strength of 420 MPa. This means that the lining material is subject to plastic deformation, which means that the mathematical description within the framework of the theory of elasticity is incorrect. The calculation carried out by considering cast iron as an elastic-plastic medium and the spatial idealization of the tubing lining allowed the actual stress state of the lining to be established. **Figure 9** shown values the distributions of maximum stress correspond to a measuring in cross-section 25 m away from the contact between the two layers, in the salt massif. The maximum stresses in the lining, in its spatial idealization, are localized on the inner ribs of the tubing in places with complex spatial geometry (stress concentrators). While the areas with minimal stresses are characteristic of the sections of the tubing connection, where the effective thickness of the structure has the greatest value. The average stresses around the perimeter of the tubing are, however, lower than in the idealization of a tubing lining in the form of an MLR.

The analysis of changes in the stress state of the lining along the height of the shaft when it is idealized as a spatial structure (see **Figure 8b**) revealed the following regularities. The maximum stress for the lining located in the dolomite layer for the section located at a distance of 5 m from the contact with the salt rocks is about 115 MPa, and for the section of 10 m about 105 MPa. The maximum stresses in the lining at the contact with the salt massif are 335 MPa. The highest stresses in the lining for a long section located in the salt massif are fixed at a distance of 20-25 m and are about 415 MPa.

Thus, based on the previous statements, it should be concluded that the obtained curves are typical for each of the considered zones and their contact. And the diagram of stress distribution along the borehole trace of the considered section is presented in **Figure 10**.

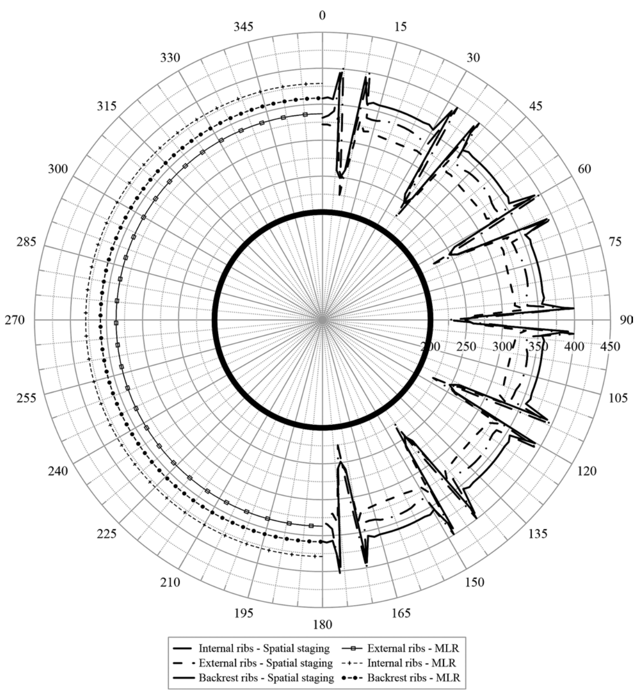


Figure 9: Stress state of tubing lining in the cross-section 25 m away from the “salt-rock” contact: a – multilayer structure; b – 3D structure.

When considering the formation of the stresses in the dolomite lining section of the shaft, it can be concluded that the difference in the results of the maximum stresses generated in the tubing lining obtained by the two modelling methods correlate well with each other. The zone of influence of the coupled layers is of the order of 5 m. In the first area, the stress values in the tubing simulation are equal in the explicit formulation, taking into account the plastic behaviour of cast iron and in the elastic formulation, primarily due to the failure to reach the yield strength of the material. The difference in the results obtained is in the range of 10-20%, whereas for an extended area at the contact of two layers the difference in results is in the range 20-50%, the maximum difference in results of 50% being at the contact of two layers. The contact area of the two layers is 10 m. This suggests that applying the methodology to determine the stresses in the shaft lining using the modelling of the cast-iron lining due to layers of different stiffness is not correct.

The formation of the stressed state of the shaft lining located in the salt massif, on its extended part, shows that the application of the elastic model of deformation of the lining material when solving the problem in the spatial statement, gives overestimated results in comparison with the use of the elastic-plastic model. The difference in the results in comparison with method 1 is in the range of 10%. A detailed examination of the obtained stress-strain diagram of cast-iron tubing lining makes it possible to conclude that the application of the MLR method of lining does not give the correct qualitative

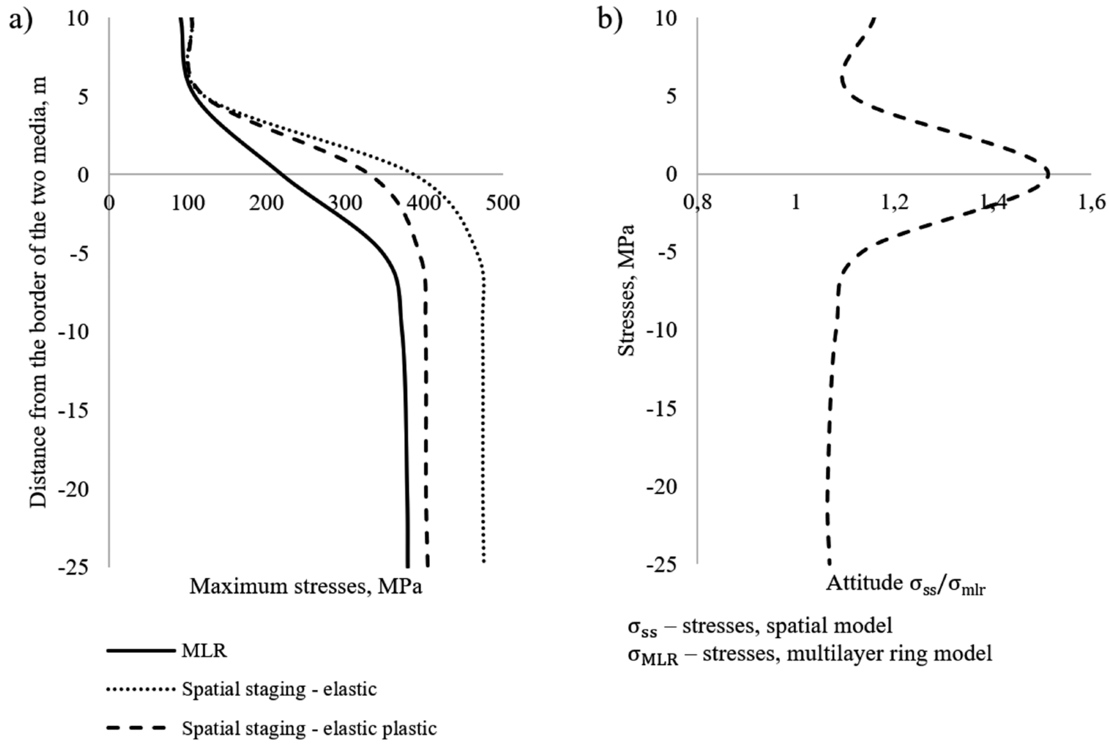


Figure 10: Comparison of stress-state prediction results with different modeling approaches: a) distribution of maximum stresses along the shaft path; b) quantitative relation between methods

assessment of stress development, at the same time the value of maximum stresses in the lining according to different methods differs by about 9%. The use of the methodology for determining the stresses in cast iron tubing lining in a spatial setting, allows an insight into the actual development of stresses to be gained.

4. Conclusions

This paper presents a methodology for predicting the stress state of vertical shaft tubing lining in the transition section between relatively strong rocks, represented by dolomites and anhydrites, and saline rocks prone to rheological processes. The methodology makes it possible to take into account such important aspects as the spatial configuration of tubings, the elastic-plastic behaviour of cast iron and the viscoplastic behaviour of saline rocks. Based on the developed methodology, a prediction of stress state of tubing lining at the transition section has been made and regularities of stress state development of the lining at different sections have been established.

On the basis of the calculations carried out, the relationship between the stress state of the lining obtained by considering the tubing lining as a multilayer structure and its spatial idealization has been established. The relationship is obtained for the section located directly in the transition zone as well as for the section located further away from the transition zone. It is obtained that the difference in the obtained results is in the range of 10-20% in the extended section of the borehole, while at the contact of two layers, the difference in the results is in the range of 20-50%.

In general, the scientific results obtained can be used to justify the parameters of tubing lining for sections of vertical shafts located at great depths. The research was performed at the expense of the subsidy for the state assignment in the field of scientific activity for 2021 **№FSRW-2020-0014**.

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SAŽETAK

Analiza stanja naprezanja obloge okna na kontaktnoj zoni anhidrita i kamene soli

Glavna problematika ovoga rada očituje se u predviđanju stanja naprezanja – deformacije kombinirane obloge vertikalnoga okna smještene na kontaktu dvaju slojeva dolomita i soli. Studija predviđa geomehaničke procese na kontaktu dolomitnoga sloja i sloja soli u blizini proširenoga presjeka vertikalnoga okna, uzimajući u obzir radni vijek okna od 50 godina. Rezultati stanja naprezanja – deformacija kombinirane četveroslojne obloge, gdje je vanjski sloj beton, a tri unutarnja sloja od lijevanoga željeza, uzimajući u obzir heterogenost, uspoređeni su s rezultatima dobivenim kada je u obzir uzeta isključivo struktura cijevi. Rješenje problema provedeno je u trodimenzionalnome sustavu. Proračun obloge cijevi, uzimajući u obzir stvarnu geometriju, povećat će točnost predviđanja stanja naprezanja obloge, što upućuje na važnost parametara obloge.

Ključne riječi:
linija, soli, opterećenje, stres, prijelazna zona, reologija, tubing

Author's contribution

Maxsim Karasev (Ph.D., Associate Professor) provided the development of methodology, processing of numerical modelling results, and design of the graphic material. **Anatoly Protosenya** (Ph.D., Professor) provided the scientific support for the relevance of the research being carried out, and introduced revisions to the text of the article. **Andrey Katerov** (PhD student) provided the numerical modelling, processed the numerical modelling results, and wrote the article. **Vladislav Petrushin** (PhD student) performed the numerical modelling, and wrote the article.