

МЕТОД ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ РЕОЛОГИЧЕСКИХ ПРОЦЕССОВ НА КОНТУРЕ ОДИНОЧНОЙ ГОРНОЙ ВЫРАБОТКИ

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Аннотация: Представлен анализ влияния параметров численной модели соляных пород на результат прогноза напряженно-деформированного состояния в зависимости от геометрии выработки в условиях использования модели ползучести Друкера-Прагера. Реализация модели выполнена методом конечных элементов, в программном комплексе Simulia Abaqus с использованием вязко-упруго-пластической геомеханической модели каменной соли. Численная модель выполнена в постановке плоской деформации – 2D с дискретизацией рассматриваемой области на четырехугольные элементы. Рассматривались усредненные горно-геологические условия проходки транспортного штreta в подстилающей каменной соли на Палашерском участке Верхнекамского месторождения калийных солей. Параметрическое обеспечение реологической модели выполнено на основе результатов инструментальных наблюдений за конвергенцией породного контура одиночной горной выработки в схожих условиях. Описан метод построения численной модели, обеспечивающей отсутствие искажений в прогнозе напряженно-деформированного состояния породного массива на контуре горной выработки, пройденной в породах, склонных к проявлению реологических свойств. Установлено, что минимальные размеры численной модели должны определяться по наибольшим линейным размерам выработки и превышать его не менее чем в 16 раз. Размер конечного элемента численной модели должен определяться по наименьшему радиусу кривизны поверхности и составлять не более одной шестой его величины. Сетка конечных элементов в окрестности горной выработки должна состоять из структурированных четырех узловых элементов, а их ребра должны быть ориентированы нормально относительно поверхности.

Ключевые слова: соляные породы, ползучесть, численное моделирование, реологическая модель, метод конечных элементов, конвергенция породного контура, модель Друкера-Прагера.

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Method of numerical modeling of rheological processes on the contour of single mine working

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Abstract: An analysis of the numerical model's parameters for saliferous rocks influence on the result of the stress-strain state prediction depending on the geometry of mine working under the conditions of using the Drucker-Prager creep model is presented in this paper. The model was realized by finite element method in Simulia Abaqus software package using visco-elastic-plastic geomechanical model of rock salt formations. The numerical model was carried out in the 2D plane deformation formulation with discretization of the considered area into quadrilateral elements. The study considered the averaged mining and geological conditions of transportation drift sinking in the underlying rock salt at the Palashersky section of the Verkhnekamsk potassium salt deposit. The parametric support of the rheological model is based on the results of instrumental observations of the convergence of the rock contour of a single mine working in similar conditions. The method of building a numerical model that ensures the absence of distortions for the stress-strain state prediction of the rock mass on the contour of the rock excavation made in rocks prone to the manifestation of rheological properties is described. It is established that the minimum size of the numerical model should be determined by the largest linear dimensions of the excavation and exceed it at least 16 times. The size of the finite element of the numerical model should be determined by the smallest radius of curvature of the surface and should be no more than one-sixth of its value. The finite element mesh in the vicinity of the rock excavation should consist of structured four nodal elements, and their edges should be oriented normal to the surface.

Key words: saliferous bedrock, creep, numerical modeling, rheological model, finite element method, rock contour convergence, Drucker-Prager model.

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Introduction

The rheological properties of saliferous bedrock are crucial in predicting the stability of mine workings. Under the influence of stresses, both time-independent elastic deformations and time-dependent creep deformations appear in them [1 – 3]. The works [4 – 6] show the necessity of application of measures to preserve the bearing capacity of mine workings at the final stages of operation of salt deposits. The main tool for solving problems related to the prediction of displacements of the contours of mine workings and the host rock mass and the development of the stress-strain state (STS) of the support caused

by displacements of the rock massif is the geomechanical description of the mechanisms of deformation of saliferous rocks [7, 8].

At present, numerical modelling by finite element method is widely used [7, 9]. The most common software products with the ability to describe creep deformations are Plaxis and Abaqus [10]. Brief characteristics of the implemented models are presented in [7, 11, 12]. Most geomechanical models are based on the description of the steady-state stage of crawling, which is due to the long-time frame of prediction [13 – 15]. Since the operating period of the mine is very long, and the main de-

velopment of deformations is within the steady-state creep, it is possible to use the Drucker-Prager creep model to describe long-term deformations by selecting its correct parameters [7, 16–18].

It is necessary to study the possibility of applying the considered model for predicting the STS of the rock salt mass and long-term deformations of the rock outline [19–21]. The current research is aimed at studying the correct use of the Drucker-Prager model, as well as at developing a technique for building a numerical model of the saliferous massif, which provides a relatively accurate prediction of rock contour displacements, on the basis of which it is possible to predict the operation of underground structures, the stability of mine workings and the STS of the underlying strata [22–24].

Numerical modelling's main stages

The prediction of geomechanical processes occurring in the vicinity of the chambers was performed in the Simulia Abaqus software package using the finite element method [25–28]. The numerical model was performed in the 2D plane deformation formulation with discretisation of the considered area into quadrangular elements. Calculation of the stress-strain state of the bedrock massive in the vicinity of a single mine shaft was performed in two steps. At the first step, the boundary conditions were set and the initial hydrostatic stress field in the intact rock mass was modelled [1, 7, 29]. In salt or clay layers, the stress state is close to hydrostatic due to their viscoelastic properties [19, 29]. In the second step, the excavation was modelled by «removing» the finite elements from the model [30].

The numerical model reflects the mining and geological conditions of the transport drift sinking at the Palashersky section of the Verkhnekamsk potash deposit. The boundary conditions in the model are

as follows: the lateral faces of the design scheme were limited in horizontal displacement, the lower and upper faces are limited in vertical displacement, which ensures displacements of the excavation surface due to instantaneous and creep deformations [31–33]. In the model, a hydrostatic stress field corresponding to the excavation depth of 425 m is specified. The generalised calculation scheme is shown in Fig. 1, a. The Drucker-Prager model is used to describe the behaviour of rock salt. The model combines visco-elastic-plastic deformations of the material (1), a schematic representation of the rheological model is presented in Fig. 1, b. The material is plasticised along an equivalent creep surface, which coincides with the yield surface [34–37].

$$\dot{\varepsilon}_{cr} = \left(A(\sigma_{cr})^n \left[(m+1)\varepsilon_{cr} \right]^m \right)^{\frac{1}{m+1}}, \quad (1)$$

where $\dot{\varepsilon}_{cr}$ – rate of relative crawling deformation; σ_{cr} – equivalent creep stress; ε_{cr} – relative creep deformation; A, m, n – creep parameters of the material given as functions of temperature and stress state.

One of the longest observation periods for the convergence of the single excavation rock contour in saliferous bedrock is 40 years and is presented in [29]. In addition to the characteristic intervals of average convergence velocities presented in [29], the values of average vertical convergence velocities of a single rock excavation measured at the observation stations at the Palashersky site were also taken into account to determine the rheological parameters of the rock salt model. It can be seen from (Fig. 1, c) that over time the results of instrumental observations numerically approach the values obtained in the model. In (Fig. 1, d), the plot of rock contour displacements in the model is compared with the characteristic one. On the prediction time plot of 40 years, the model shows a fairly good convergence,

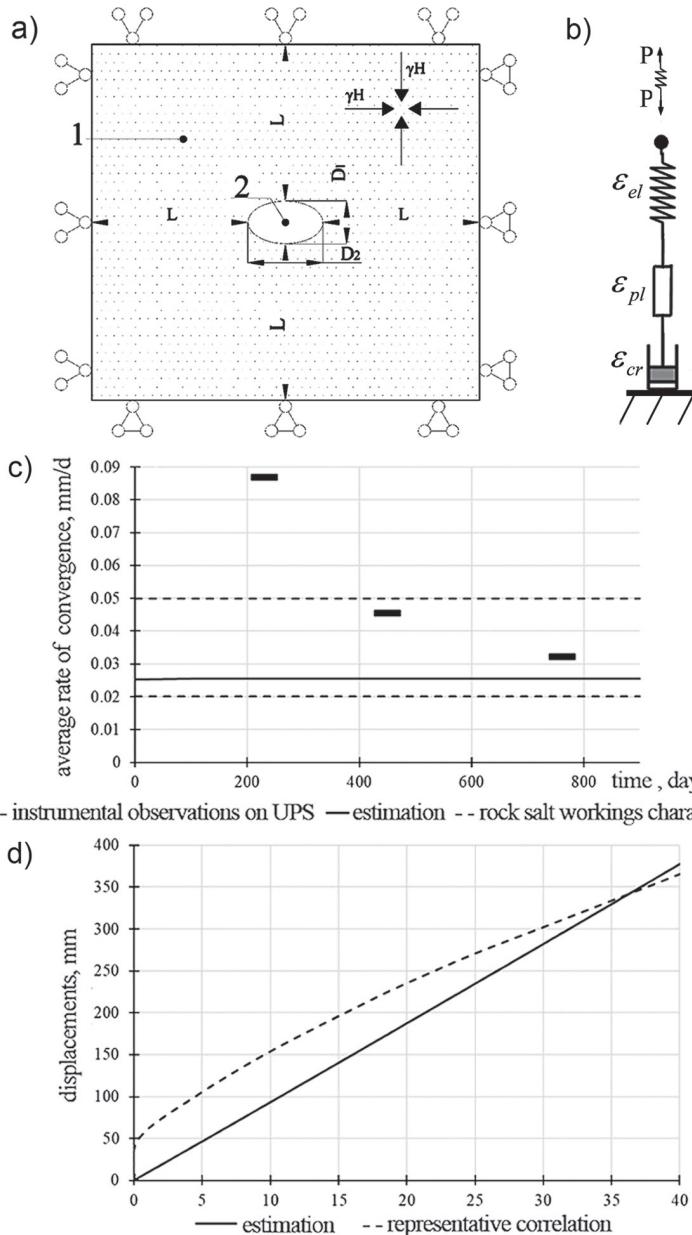


Fig. 1. Verification of the rheological model for rock salt: estimated scheme for multivariate modeling; 1 – rock salt massif; 2 – single mine excavation (a); schematic representation of the Drucker-Prager rheological model; ε_{el} , ε_{pl} , ε_{cr} – elastic, plastic and viscous deformations, respectively (b); graph of the dependence of the average rate of convergence of the rock contour of the single mine excavation (c); horizontal displacements of the single excavation lateral surface (d)

Рис. 1. Верификация реологической модели каменной соли; расчетная схема к многовариантному моделированию; 1 – массив каменной соли; 2 – одиночная горная выработка (а); схематическое представление реологической модели Друкера – Прагера; ε_{el} , ε_{pl} , ε_{cr} – упругие, пластические и вязкие деформации соответственно (б); график зависимости средней скорости конвергенций породного контура одиночной выработки (в); горизонтальные смещения боковой поверхности одиночной выработки (г)

Table 1

Rheological Drucker-Prager model's parameters for rock salt
Параметры реологической модели каменной соли Друкера-Прагера

Angle of shear friction, β , deg.	Fluidity factor, K	Dilatancy angle, ϕ , град	A	n	m
54	1	10	$5 \cdot 10^{-10}$	0.7	-0.59

with an error of 3.1%. Rheological rock salt model's parameters (Table 1) provides displacements of the rock contour of a single excavation with a steady constant velocity, which is in the range of velocities characteristic of the given conditions and the rocks under consideration – rock salt, from 0.02 to 0.05 mm/day [29].

The rheological model of rock salt serves as a tool for determining the influence of the model boundaries and its geometrical parameters on the result of predicting the STS of the host rock mass with rheological properties [19, 31, 38]. Due to the small amount of data on the convolution of the rock contour of the excavation, it is possible to determine the model parameters based on the convergence of the intensity of displacement development over a sufficiently large prediction time interval, up to 40 years [29].

In order to analyse the influence of model parameters on the forecast results, the method of multivariate modelling was used. The results obtained in the models with different distances from the mine workings to the model boundaries, from 3 to 38 diameters were considered. Finite element sizes varied from 0.125 to 1 m. The models consider circular cross-sections with a diameter of 3.1 m and elliptical cross-sections, with the ratio of the larger diameter to the smaller diameter ranging from 1.1 to 1.75.

Initially, the results of the circular mining model were analysed to identify patterns in the results. Having identified the distance interval of interest between the excavation contour and the model boundaries, the elliptical cross-sectional mining models are considered at the second stage. Due to the axisymmetric formulation of the problem, the results obtained in the circu-

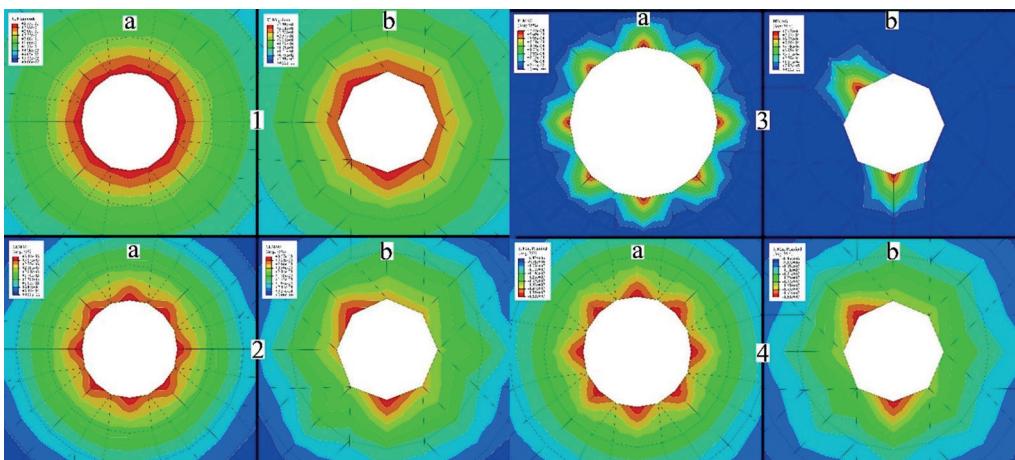


Fig. 2. Example of prediction results distortions: models with element size 0.5 m (a); models with element size 1 m (b); 1 – displacements; 2 – creep deformations; 3 – plastic deformations; 4 – maximum stresses

Рис. 2. Пример искажений результатов прогноза: модели с размером элементов 0.5 м (а); модели с размером элементов 1 м (б); 1 – смещения; 2 – деформации ползучести; 3 – пластические деформации; 4 – максимальные напряжения

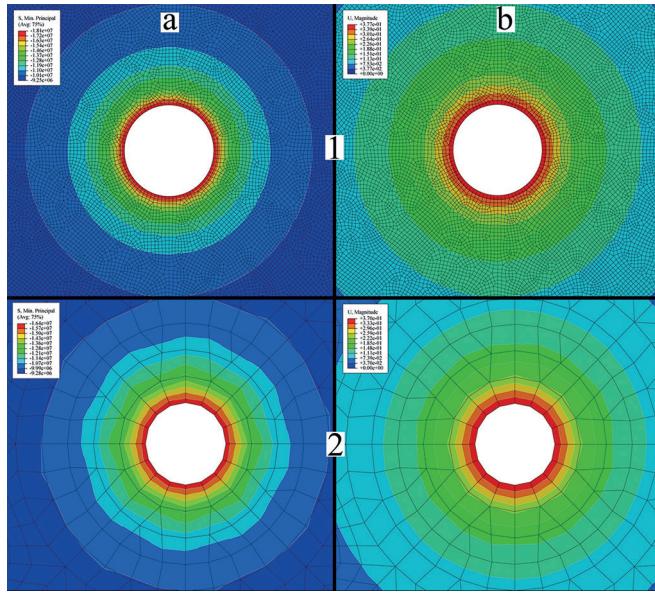


Fig. 3. Example of stress-strain state prediction with one row of structured elements of the first order; maximum stresses (a); displacements of the excavation contour (b); 1 – distance from the excavation contour to the model boundaries of 8 diameters, element size 0.125 m; 2 – distance from the excavation contour to the model boundaries of 26 diameters, element size 1 m

Рис. 3. Пример прогноза НДС с одним рядом структурированных элементов первого порядка; максимальные напряжения (а); смещения контура выработки (б); 1 – расстояние от контура выработки до границ модели 8 диаметров, размер элемента 0.125 м; 2 – расстояние от контура выработки до границ модели 26 диаметров, размер элемента 1 м

lar-section mining models are identical in all radial directions. In the case of the elliptical cross-section model, the distribution of stresses and displacements on the contour is formed in accordance with the orientation of the main diameters of the mine working.

During the modelling results' processing, distortions in the element nodes on the mine contour and in its vicinity, which are not peculiar to elastic-plastic models, were revealed. They are reflected in the predictions of displacements of the rock contour, creep deformations, plastic deformations and stresses. Examples of distortions of the prediction results and the finite element contour are shown in Fig. 2, which allows to correlate the distortions and the element grid. It can be seen from the presented epurées that elements orientated not normal to the deformed surface result in non-uniform

stress distribution. Consequently, it can be concluded that for correct prediction of the STS of rocks prone to rheological properties, it is necessary to break the model in the vicinity of the deformed surface with a structured mesh of quadrangular finite elements of the first or second order. The elements should be normally orientated to the deformed surface. From the results of the STS prediction, Fig. 3, we can see that one row of structured finite elements on the deformed contour is sufficient to exclude local stress extremes on it.

To determine the sufficient distance to the model boundaries and finite element dimensions, 45 models were calculated. Considered sizes of finite elements, Δ : 1, 0.75, 0.5, 0.25, 0.125 m, considered distances to the model boundaries: 3, 5, 8, 10, 16, 19, 26, 32 and 39 diameters of mine workings (3.1 m).

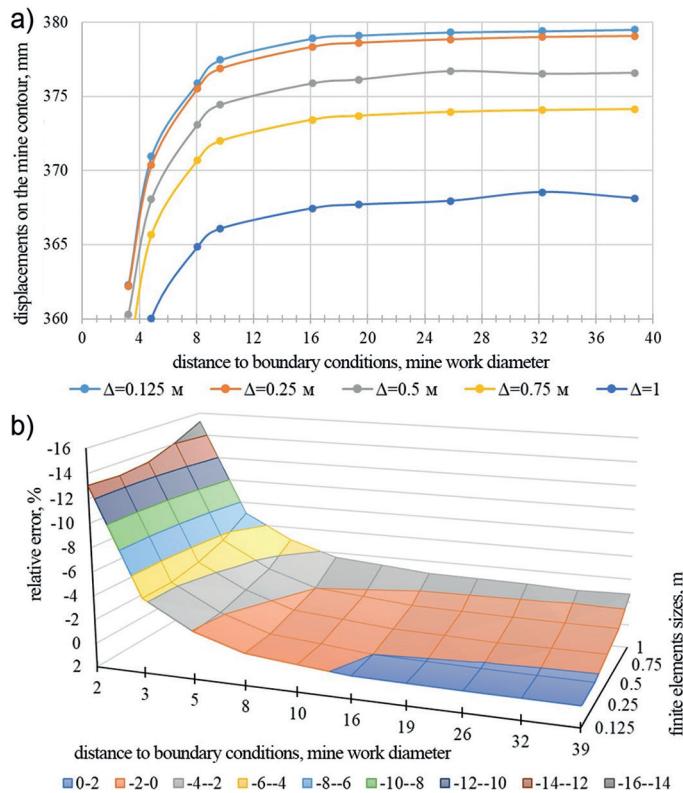


Fig. 4. Displacement values on the mine contour based on the multivariate modeling results: resulting displacements (a); relative error in the prediction results, color indicates the error value (b)

Рис. 4. Величины смещений на контуре выработки по результатам многовариантного моделирования: результирующие смещения (а); относительная погрешность в результатах прогноза, цветом указана величина погрешности (б)

Let us consider the resulting displacements on the mine contour at the end of the prediction (Fig. 4, a). Here we can see a more distinct convergence in the results as the size of the finite elements decreases. At a distance of 16 mine diameters, the difference in the predicted displacement of the mine contour in the models with 0.125 and 0.25 m elements is 0.15%. This distance to the model boundaries is characterised by a flattening of the graph.

Taking into account the above mentioned, the most rational parameters of the numerical model will be the size of the finite element 0.25 m, (0.8 diameters of the excavation) and the distance from the deformed surface to the model boundari-

es 16 diameters of the excavation. Characterising these parameters as recommended, it is possible to calculate the relative error in the prediction results in models with different parameters (Fig. 4, b).

Thus, certain parameters of the model provide sufficient accuracy in predicting the STS of rocks prone to rheological properties and exclude the occurrence of distortions in the vicinity of the deformed surface.

To verify the defined model parameters, we consider elliptical cross-sectional excavations. Let us assume the sizes of finite elements, 0.5, 0.25, 0.125 m, distances to the boundaries of the model, 0.5, 0.25, 0.125 m.: $10 \cdot D_1$, $16 \cdot D_1$, $16 \cdot D_2$, $20 \cdot D_2$, where D_1 , D_2 – main diameters of

the excavation, equal to 4 and 7 m, respectively. The prediction of deformations and displacements in the vicinity of the mine in the areas where it has the largest linear dimensions depends on the values of these values. Thus, the optimal distance from the deformed surface to the model boundaries is determined by the largest linear size of the mine.

Let us consider the model region in the vicinity of the smaller linear dimension of the mine — the sides of the mine and the larger — the roof. In (Fig. 5, *a*, *b*) the resulting displacements on the contour of the mine workings at the end of the prediction are presented. They show similar convergence of the results as in the case of a circular cross-section mine. The convergence of the displacement prediction results for

the finite element sizes of 0.125 m and 0.25 m is comparable to the previously discussed results, as well as the error in the prediction of creep deformations.

Let us analyse the influence of the finite element size on the results of massif STS prediction in the vicinity of the excavation contour depending on the ratio of excavation width to height, in the model — larger and smaller diameter. We consider excavations with the following diameter ratios: 1:1; 1:1.2; 1:1.33; 1:1.67 and 1:1.75, the sizes of finite elements ranging from 0.05 to 0.68 smaller than the radius of the excavation.

The results of the rock contour displacements prediction and values of long-term creep deformations lie on exponential approximating curves (2), connecting them to form a surface (Fig. 6, *a*). Relative

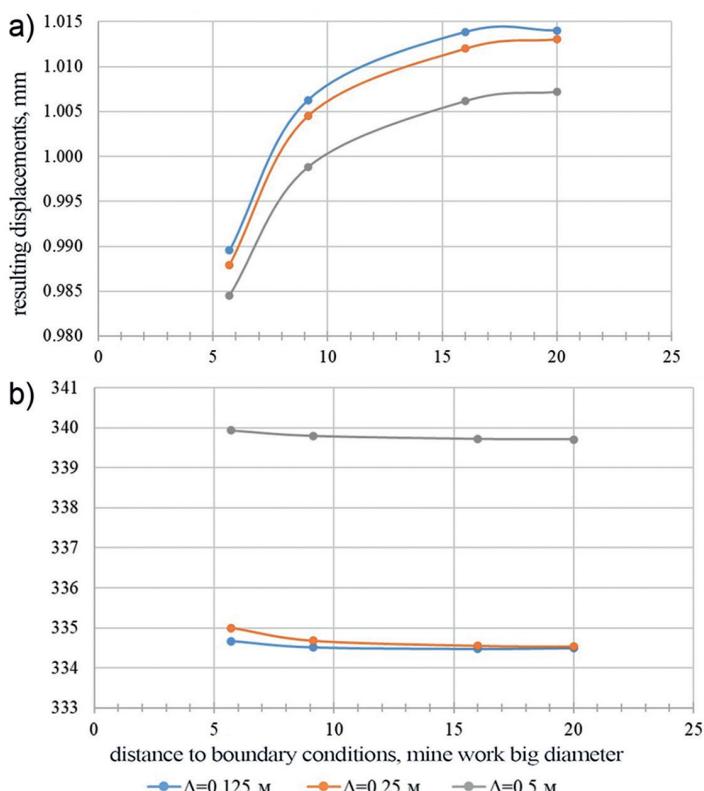


Fig. 5. Resulting displacements on the mine contour: zone of larger linear size (*a*); zone of smaller linear size (*b*)

Рис. 5. Результатирующие смещения на контуре горной выработки: зона большего линейного размера (*a*); зона меньшего линейного размера (*b*)

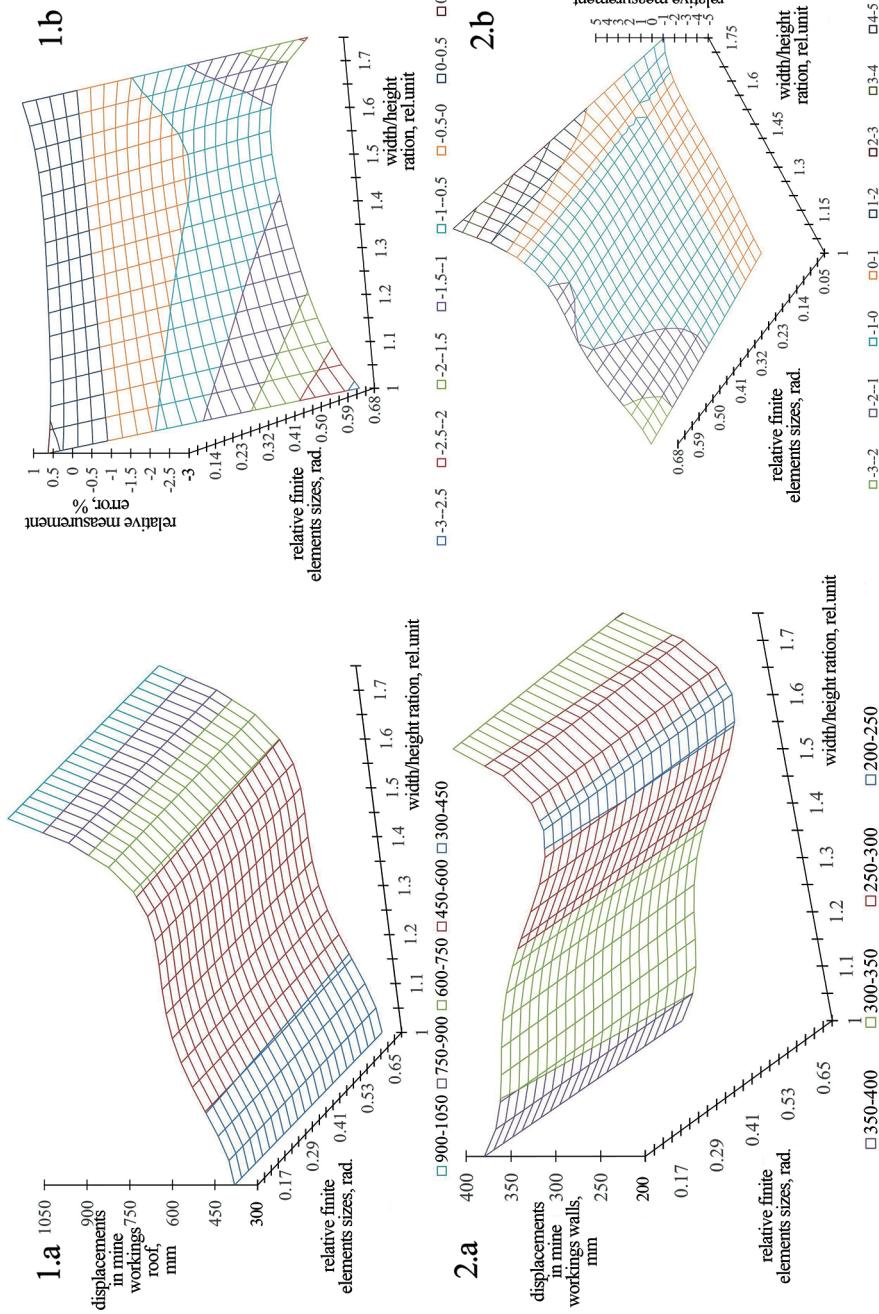


Fig. 6. Resulting displacements of the rock contour: 1 – vertical displacements in the roof of the excavation; 2 – horizontal displacements in the sides of the excavation; Resultant displacements (a); relative deviations in the results; the color indicates the calculated value (b)
 Рис. 6. Результатирующие смещения городного контура: 1 – вертикальные смещения в кровле выработки; 2 – горизонтальные смещения в боках выработки; результатирующие смещения (а); относительные отклонения в результатах; цветом указана расчетная величина (б)

deviations in the prediction results from those in the models adjusted according to the recommended parameters are presented in the form of a surface (Fig. 6, b)

$$u = A \left(\frac{d_1}{d_2} \right) \cdot e^{-B \left(\frac{d_1}{d_2} \right) \Delta}, \quad (2)$$

where u — displacements of the mine workings rock contour for the end of forecast period, mm; Δ — finite element dimensions, smaller radius of excavation; $A(d_1/d_2)$, $B(d_1/d_2)$ — coefficients reflecting the ratio of the main diameters of the excavation.

The results show that as the difference between the main diameters of the excavations increases, the influence of the finite element size increases. Increasing the finite element size leads to a decrease in the displacements of the rock contour in the region of larger diameter and to an increase in the displacements in the region of smaller diameter. The effect of hardening of the material is manifested, because in the conditions of the considered models vertical displacements in the roof of the excavation due to the geometry of the calculation scheme prevent the progression of horizontal displacements in the sides of the excavation. The recommended size of the finite element ensures the absence of these errors in the prediction.

Conclusions

The study considered the mining and geological conditions of a transport tunnel in rock salt at the Palashersky section of the Verkhnekamsk potassium salt deposit.

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The influence of the finite element size and rock model depending on the excavation geometry on the result of prediction of the rock mass STS in the vicinity of the excavation for the Drucker-Prager creep model was analysed. The parameters of the rheological model providing sufficient convergence of the results of the rock wall convolution prediction with in-situ data were determined.

The work defines the method of building a numerical model of the mass, which provides a reliable forecast of STS of the mine excavation made in rocks prone to the manifestation of rheological properties.

1. The distance from the deformed surface to the model boundaries in all directions shall be determined by the largest linear dimensions of the excavation and shall exceed it by at least 16 times.

2. The size of the finite element of the numerical model shall be determined by the smallest radius of curvature of the surface and shall not exceed one sixth of its value.

3. The finite element mesh in the vicinity of the deformed surface should consist of structured four nodal elements, and their edges should be orientated normal to the surface.

The given method of building numerical models provides a reliable prediction of rheological processes in the vicinity of the mine workings. The methodology for predicting the integrity of the interstage integrity using a similar numerical model of interchamber pillars is a promising research development direction.

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