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GEOMECHANICAL SUBSTANTIATION OF PARAMETERS OF TECHNOLOGY FOR MINING SALT DEPOSITS WITH A BACKFILL

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Abstract: The analysis of the technogenic impact of mining on the environment was carried out. A transition to geotechnology with backfill is proposed in order to reduce the impact of mining operations. The paper presents the results of research aimed at finding the parameters of the technology for mining salt deposits with backfill and the determination of the backfilling influence on the dynamics of deformation of the undermined rock mass. The results of studies on the qualitative and quantitative assessment of the rock mass behavior (by the finite element method with the use of the FLAC3D software), extracted by the harvesters, are given. The research shows the influence of mining on the mass, changes in the maximum stresses during the cementing of the paste backfill in the stopes. It is recommended to use this approach in geotechnical assessment of the rock mass behavior in the conditions of using development systems of various classes.

Keywords: *geotechnology, backfilling operations, rock mass, mathematical modeling, stress–strain behavior*

1. INTRODUCTION

The consumption of mineral resources increases every year. It can be stated that resource consumption is close to exponential along with the exponentially growing population of the Earth. We also observe a sharp increase in the depth of deposit development. If in

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the last century, the depth of development rarely exceeded 1.5 km, and at present, the depth of mining operations in some deposits (Mponeng Mine, TauTona Mine, Bambanani Mine – Republic of South Africa, Kidd Mine - Canada) reaches 4 km. Mineral extraction is carried out at a depth of more than 1.5 km in Russia and in Eastern Europe (mine named after Lenin, mine "Rodina" – Ukraine, mine "Cheremukhovskaya--Glubokaya", mine "Taimyrsky" – Russia). In addition, reserves that were previously classified as off-balance are involved in development: the development of reserves, which is not economically efficient (with a low content) at the time of assessment according to technical and economic calculations; located within water protection zones, settlements, structures, agricultural facilities, sanctuaries, natural, historical and cultural monuments. All that leads not only to the increase in the cost of ensuring the technological process of mineral extraction, enrichment and primary processing, but also to the increased risk of rock pressure in unpredictable forms. Rational geotechnology already at this stage is obliged to create a foundation and to initiate the advanced development of science in the integration of mining experience and scientific and technological knowledge. In addition, due to the growing need for mineral resources and the limited capacity of the biosphere, the Earth's surface is experiencing an enormous man-made load (Golik et al. 2017). Due to the limited biosphere's ability of self-regulation and self-reproduction, it is necessary to create sparing technologies that ensure sustainable development of mining (Sidorova 2019). Mining waste, as well as concrete recycled from demolition works in civil engineering, may be suitable for use in large-scale earthworks, provided it has a neutral impact on the environment with respect to the spread of chemical contamination or other sources of pollution (Zástěrová et al. 2016). Several attempts of land planning with particular regard to the potential use of hard coal tailing dumps were presented at VŠB – Technical University of Ostrava (Czech Republic) (Niemiec et al. 2017).

When minerals are extracted, the natural state of the rock mass changes, which leads to a redistribution of stresses in it and causes the development of cracks (Baryakh et al. 1994). In some cases, the development of cracks reaches daylight area which leads to collapse or to the disruption of waterproof strata and water breakthrough into the mine (Adigamov, Khairutdinov 2008) (Fig. 1).

Improving the organization of actual mining will increase the completeness of excavation, reduce the cost of mining and, at the same time, reduce the negative impact of geotechnology on the environment. Inaccurate and erroneous calculations lead to incorrect decision-making, which, in turn, causes the wrong choice of mining technology. An incorrectly selected development technology or incorrectly calculated parameters lead to the integrity and leakproofness violation of large aquifers. This is the reason for flooding of underground structures, a significant deterioration in mine safety and a change in the hydrogeological situation of the deposit (Kongar-Syuryun et al. 2020).

Similar problems are observed in the construction of various facilities. Some examples were given in works where the causes of rocky landslides (Sanz-Pérez et al. 2016) and sinkholes of karst formations (Sanz et al. 2016) were considered. Landslides and sinkholes cause vibrations that affect the environment (Dobrzycki et al. 2019a). Methods for reducing vibrations were considered in Dobrzycki et al. (2019b).

Fig. 1. Failure at the mine of the company "Uralkali", Russia, Perm region

The use of mining and construction waste is an important issue worldwide (Golik et al. 2017), (Kongar-Syuryun et al. 2020), (Khayrutdinov et al. 2020a). But it has a very local size and value. Kawalec et al. 2017 consider the possibility of using large volumes of man-made waste (crushed waste rock from dumps) for great infrastructure projects: roads and railways, flood protection systems – dams. In this regard, it is possible to identify the factors to be taken into account when using industrial waste:

1. Suitability of the waste in terms of its strength and environmental "cleanliness";
2. Financial costs of preparation for implementation (crushing, sorting, producing a mixture, forming a mass, and so on);
3. Availability (presence in the right place, at the optimal time and in the required volume);
4. Environmental costs (transportation, storage, processing, etc.).

Deposit development using cemented paste backfill of mined-out void allows to solve the issues of mining deep horizons, using a combined mining method, effectively managing rock pressure, preserving the waterproof strata and eliminating the formation of failures on the daylight area (Khayrutdinov et al. 2020b), which leads to an increase in the safety of mining operations (Golik, Burdzieva 2016). Geotechnology with a backfilling allows to get the following economic effects: an increase in the life of the mine; an increase in the completeness of the excavation. The use of man-made waste in the backfill mixture allows to get a number of environmental effects: preservation of the daylight area; utilization of man-made waste; reducing the harmful impact of waste on the environment (Golik et al. 2018). And together with the following economic results: no expenses for the construction of waste rock dumps and tailings, the exclusion of environmental charges and others will lead to a multiplier effect (Novoselov et al. 2017).

2. SELECTION OF THE OBJECT AND SUBJECT OF RESEARCH

When applying the technology with a backfill of mined-out void, it is necessary to address several main issues:

- determine the optimal strength characteristics of the fill mass after cementing;
- determine the composition of the backfill material;
- solve the problem of completeness of a backfill of mined-out void with the fill material.

Thus one of the main tasks of modern geotechnology is to develop a methodology for calculating the strength characteristics of the fill mass, to create a model of mineral extraction process and to model the processes that occur during the extraction of a mineral.

The main indicator of the fill mass is its strength after cementing, in the calculation of which modern methods are based on numerical modeling.

The most acute issue at present is the development of salt deposits. To develop these deposits, a stoping with rib pillar is used. The considered development system has several disadvantages:

1. Loss of minerals up to 65%;
2. Deterioration of the environment due to the large volume of man-made waste;
3. Constant redistribution of rock pressure due to the presence of voids and plasticity of pillars;
4. Violation of the daylight area due to the destruction of pillars and the formation of failures;
5. Violation of the waterproof strata and flooding of the mine.

During the development of potash deposits and subsequent processing of the extracted ores, a large amount of man-made waste is formed, which is stored in tailing dumps on the surface (Sanz et al. 2016). The use of geotechnology with cemented backfill during the development of potash deposits will eliminate a number of drawbacks that have arisen earlier. The use of enrichment wastes, which includes NaCl with KCl, $MgCl_2$ or $CaSO_4$ admixtures as an aggregate was discussed earlier in the works (Kongar-Syuryun et al. 2020), (Khayrutdinov et al. 2020a), (Khairutdinov, Votyakov 2007), (Votyakov 2009), (Shang Pengqiang et al. 2011), which indicates high relevance. When creating a fill mass based on waste from potash ore processing, various components were used as a binder: cement (Kongar-Syuryun et al. 2020), (Khayrutdinov et al. 2020a), (Khairutdinov, Votyakov 2007), (Votyakov 2009), (Xuquan Huang et al. 2014); slags (Khayrutdinov et al. 2020c). The use activation processing of components (Kongar-Syuryun et al. 2020), (Khayrutdinov et al. 2020a), (Shang Pengqiang et al. 2011), (Ermolovich, Ermolovich 2016) with preliminary re-processing is proposed (Golik et al. 2020) to improve the properties of paste backfill components and increase the characteristic strength of the mass.

Modeling is increasingly used to predict various situations. Currently, modeling of various processes in all fields of science, production, politics is becoming more widespread (Kalinsky et al. 2019).

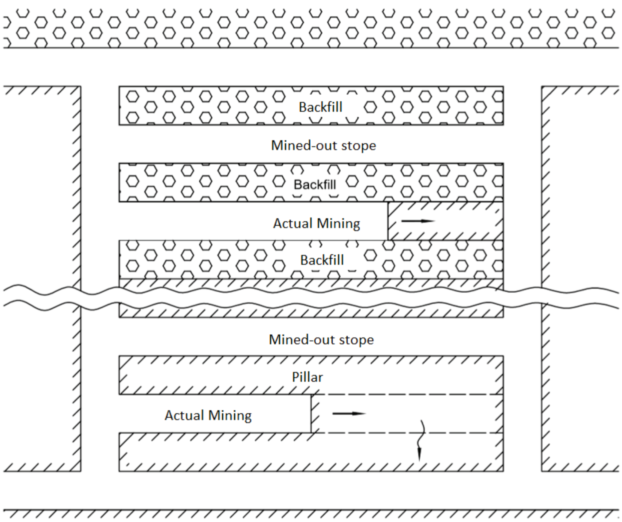

Fig. 2. Stoping with rib pillar and backfilling
for thin and moderately thick horizontal deposits

For research in this work, three-stage stoping with rib pillars and backfill (Fig. 2) is taken as an object of modeling. In this case, the maximum completeness of mineral extraction with the least losses is achieved at the average thicknesses of the ore body.

3. STATEMENT OF THE PROBLEM

The subject of the research is the substantiation of the parameters of the technology for the salt deposits development and the determination of the strength characteristics of the fill mass, as well as the establishment of the actual mining impact on the strain changes in the undermined salt mass. Geotechnology with backfill will minimize the cracks development in the undermined salt mass, ensure the safety of the waterproof strata, and, as a result, protect the mine from emergency flooding. Special attention is paid to the completeness of the extraction and the use of enrichment waste in the backfill, which will lead to an improvement in the qualitative and quantitative indicators of extraction and a reduction in man-made waste on the surface.

The starting point for modeling the processes is an intact rock mass.

The deposit is mined by stoping with rib pillar. A block is extracted by stopes 4 m wide and to 200 m long, with 8 m wide rib pillar. The mined-out stopes are filled with cemented paste backfill in the proposed model. Extraction from the rib pillar is executed in two stages. At the first stage, part of a pillar, i.e., $^{1}/_{2}$ its width, is extracted between mined-out stopes with subsequent backfilling with cemented mixture.

At the second stage, the remaining part of the pillar is extracted. After that, the mined-out void is left open or filled with backfill (Table 1).

Table 1. Sequence of mining operation

Stope number	1	2	3	4	5	6	7	8	9
Extraction stage	I	II	III	I	II	III	I	II	III
Stope width, m	4	4	4	4	4	4	4	4	4

Stage I (yellow): actual mining of stopes 1, 4, 7 with backfilling.
Stage II (green): actual mining of stopes 2, 5, 8 with backfilling.
Stage III (blue): actual mining of stopes 3, 6, 9 with backfilling.

In addition to ensuring safe mining operations, the selected stope and pillars width must ensure the effective use of mining equipment. When using backfill for stoping with rib pillar, it becomes possible to simultaneously mine several stopes along one conveyor line. This increases productivity, and the backfill of mined-out void reduces losses. Also, this technology allows to regulate the time of cementing the fill mass to the design strength. The fill mass reaches maximum strength after 90 days. The model used a strength gain period of 60 days. Taking that value, it means that the time gap when extracting adjacent stopes was 70 days, taking into account mining and filling operations. The development depth is 1200 m.

The mining operations plan is shown in Table 2. As may be concluded from the table, the exposure time is 10 days, during which the stopes will be extracted (5 days), backfilling operations will be prepared and carried out (5 days).

Table 2. The mining operation plan

	Stage/Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	69	70
1	I	1	2	3	4	5	6	7	8	9	10	1	2	3	4	59	60
2	II																
3	III																
4	I		1	2	3	4	5	6	7	8	9	10	1	2	3	58	59
5	II																
6	III																
7	I			1	2	3	4	5	6	7	8	9	10	1	2	57	58
8	II																
9	III																
	Stage/Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	69	70

	Stage/Day	71	72	73	74	75	76	77	78	79	80	81	82	83	84	139	140
1	I																
2	II	1	2	3	4	5	6	7	8	9	10	1	2	3	4	59	60
3	III																
4	I	60															
5	II		1	2	3	4	5	6	7	8	9	10	1	2	3	58	59
6	III																
7	I	59	60														
8	II			1	2	3	4	5	6	7	8	9	10	1	2	57	58
9	III																
	Stage/Day	71	72	73	74	75	76	77	78	79	80	81	82	83	84	139	140

	Stage/Day	141	142	143	144	145	146	147	148	149	150	151	152	153	154	209	210	211	212
1	I																		
2	II																		
3	III	1	2	3	4	5	6	7	8	9	10	1	2	3	4	59	60		
4	I																		
5	II	60																	
6	III		1	2	3	4	5	6	7	8	9	10	1	2	3	58	59	60	
7	I																		
8	II	59	60																
9	III			1	2	3	4	5	6	7	8	9	10	1	2	57	58	59	60
	Stage/Day	141	142	143	144	145	146	147	148	149	150	151	152	153	154	209	210	211	212

Extraction and filling stopes – 10 days.
Strength gain period – 60 days.

Before starting the model construction, analytical calculations of the elastic properties (Young's modulus, Poisson's ratio and strength characteristics of uniaxial compression) of the backfilling were carried out with the derivation of the time, loads and strains derivation. This determines the interaction of overlying strata on the fill mass, taking into account the change in the strength characteristics of the backfill in time.

Taking into account the strength gain parameters of the backfill, along with the dependence on pressure, there is also an additional dependence of cementing and strength on time.

The composition of the backfill mixture is determined based on the results of studies on uniaxial compression and endometrium. The composition of the backfill mixture depends on the characteristic strength of the mass and the rate of strength gain during cementing. In addition, when choosing the composition backfill mixture, it is necessary to take into account the additional heating of the air in the stopes during hydration and the volume of drainage. In this model, the stope fill coefficient with filling material was taken to be 100%.

4. METHODS AND CALCULATING THEORY

Earlier, the assessment of the stress–strain behavior of the mining system was carried out during the extraction of steeply salt deposits. The research results obtained from the quantitative assessment of the mass behavior were used (Barton's method) (Eremenko 2018). An analysis of the potential for crack development was considered in (Baryakh et al. 1994) under state of plane strain.

The Finite-Element-Methode (FEM) is widely applied when using the scheme of Roschlau and Heintze (Roschlau, Heintze 1980) for solving problems of solid bodies that can change the surface area, shape, volume, internal structure under the action of external forces. Numerical modeling and Finite-Element-Method is widely used in mining and geomechanics. On the basis of the Finite-Element-Method, ITASCA Consulting Group, Minneapolis has developed the FLAC3D 5.01 program, which implements the idea of the existing system that differs from the real model, but is much closer to the algorithmic description.

To reduce the modeling time and avoid the influence of depth on the modeling results, a pseudo-volume model is used since during modeling the depth axis is calculated in small values (up to 1 meter). This model takes into account all the parameters of the mass under study that characterize its properties and the dynamics of changes over time.

Using FEM in the FLAC3D 5.01 stresses and strains of various solids that arise as a result of internal and external forces are modeled, and their calculated values are produced. In addition, complex structural formations are investigated. The requirements for the strength characteristics of the fill mass depend on the characteristics of the overlying rocks of the extracted mass and are determined by the maximum rock pressure that affects the filled stopes. The rock pressure calculations are performed using software based on the Finite-Element-Methode. The program FLAC3D version 5.01 (ITASCA Consulting Group, Minneapolis) was used for the current study. FLAC3D 5.01 (fast analysis of Lagrange continua in 3 dimensions) was used to build three-dimensional models of various nonlinear materials properties, since it is based on well-defined modeling parameters.

The program FLAC3D has a Library or DataBase of equations to describe various material properties and their changes. In this case, it is possible to build models taking into account various factors:

- cementing time;
- plastic (material breakage criteria) and / or creeping properties of the mass;
- strength gain time of the fill mass;
- elastic properties of the fill mass;
- elastic or plastic properties of ores and adjacent strata.

5. MODEL CONSTRUCTION AND BOUNDARY CONDITIONS

According to the modeling methodology developed by Itasca Consulting Group, the geometric dimensions of the model are 5-8 dimensions of the studied object (FLAC3D Theory and Background. Minneapolis, 2013). The modeling area under consideration consists of 9 stopes 4 meters wide and 4 meters high, where the depth (distance along the Y axis) is 1 meter, since this model is presented as 2.5 D.

Accepted geometric parameters of the model (Fig. 3):

- width – 180 meters (*X*-axis), depth – 1 m (*Y*-axis),

where the thickness of the geological seam is:

- overlying strata of the roof (red) – 40 m,
- mined salt seam (green) – 4 m,
- the underlying bedrocks of the soil (blue) – 10 m.

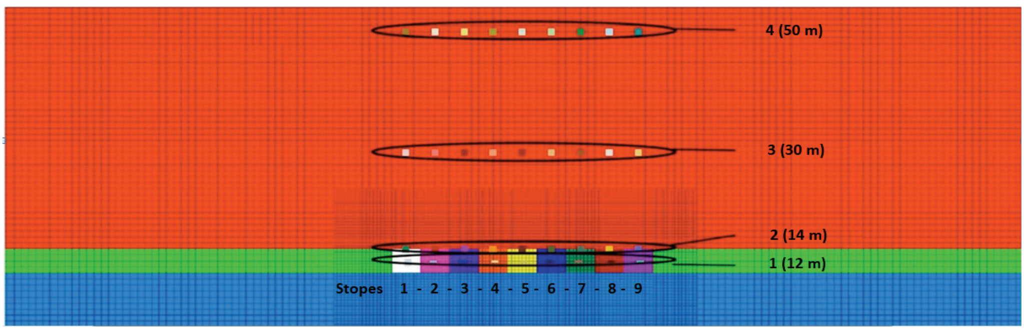

Fig. 3. *In-situ* measurements (FLAC3D, 5.01, 2019)

For the purpose of research, the height of the underlying bedrocks was taken to be 10 meters, since the rocks in the mining soil have a significant impact on the dynamics of the redistribution of rock pressure loads.

Previously, the research used an ideal elastic-plastic model, which is a generalization of an elastic and rigid-plastic medium with internal friction (Baryakh, Telegina 2013). The research was based on the strain determination of the overlying strata of the roof and the maximum stresses depending on time. When modeling the material of the salts, linear elastic strain and stationary creep were assumed. For creep modeling the Norton function was used in the form of a Power Law dependence (Baryakh et al. 1994), which allows reproducing the behavior of dominant creep. But this function does not take into account the creep symptoms caused by transient processes or damage. The geothermal gradient is taken into account by structural parameters in combination with the Arrhenius equation based on the assumption of a uniform temperature of rocks. The material and its characteristics are shown in Table 3.

Table 3. Physical and mechanical properties of materials in the model (creeping properties)

Description	Thickness [m]	Density [kg/m^3]	Poisson's ratio [–]	E-module [MПa]	Structural parameters [1/c]	Range of stress [–]
Halite of the roof	40	2150	0.24	21300	1.65E – 15	5.3
Potash seam	4	2000	0.20	19200	9.27E – 15	5.8
Halite in the soil	10	2150	0.25	18900	9.28E – 14	3.7

Source: Itasca.

Table 4. Physical and mechanical properties of fill mass (elastic properties)

<table>
<tr><th>Description</th><th>Density [kg/m^3]</th><th>Poisson's ratio [–]</th><th>Pressure [MPa]</th><th>E-module [MPa]</th><th>Time [c]</th><th>E-module [MPa]</th></tr>
<tr><td rowspan="9">Backfill (enrichment waste, cement)</td><td rowspan="9">2000</td><td rowspan="9">0.23</td><td>0.0</td><td>25</td><td>0</td><td>75</td></tr>
<tr><td>0.6</td><td>50</td><td>30</td><td>150</td></tr>
<tr><td>1.2</td><td>75</td><td>90</td><td>300</td></tr>
<tr><td>2.5</td><td>100</td><td>3600</td><td>300</td></tr>
<tr><td>5.0</td><td>125</td><td colspan="2" rowspan="5"></td></tr>
<tr><td>10.0</td><td>150</td></tr>
<tr><td>20.0</td><td>250</td></tr>
<tr><td>40.0</td><td>600</td></tr>
<tr><td>80.0</td><td>1200</td></tr>
</table>

The elastic material model was used to simulate the backfill in FLAC3D (*FLAC3D Theory and Background*, Minneapolis 2013), where the elastic modulus for different values of pressure and time is given in Tables 3 and 4. The modeling which takes into account linear elastic strain and stationary creep for ores, adjacent strata and backfill elastic strain makes it possible to adapt the behavior of the solid material of the backfill in the simulation in accordance with the test results. The effective modulus of elasticity is interpolated from Tables 3 and 4. The coefficients shown in Table 4 are taken from the results of Votyakov's research (Votyakov 2009).

6. MODELLING RESULTS

Figure 4 shows data from measurement point 2 (at the roof). In this graph, it can be observed that the maximum strain of the roof was in stope 3 and amounted to 0.506 meters, and the minimum in stope 4 was 0.450 meters. Although in stopes 1 and 9 the roof strain was the smallest, they were excluded from analytical studies due to the fact that the purity of the experiment was violated in them, namely: these stopes are adjacent to an intact mass, which has a significant impact on strain.

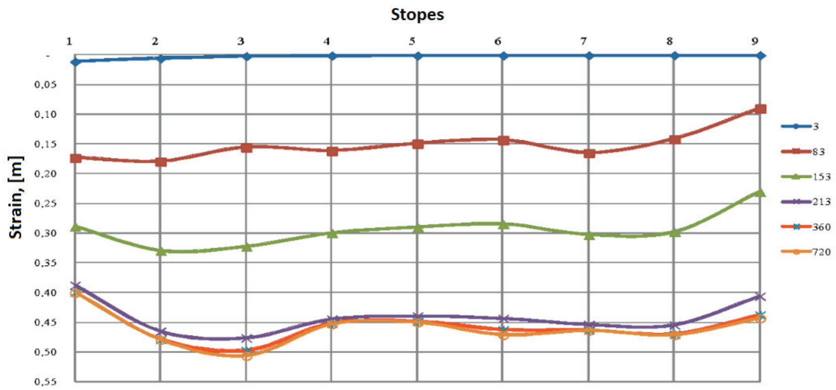

Fig. 4. Deformation in the measurement point 2 (in the roof at around 14 m) depending on the time

The modeling results showed that 95% of the maximum convergence of the roof occurs before 213 days, after which the roof "sits down" on the fill mass, which takes the pressure of the overlying strata on itself.

Changes in the maximum stresses at the measurement point 2 (in the roof) for different stopes are shown in Fig. 5. It can be seen from this graph that a sharp change of the stress state in the roof continues up to 213 days. That indicates that at this time there was a final redistribution of rock pressure, which is confirmed by the previous study of strain (Fig. 3).

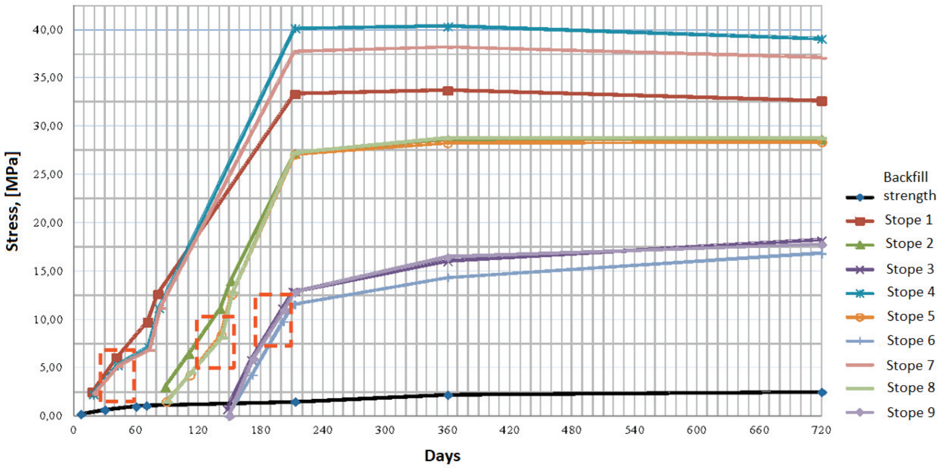

Fig. 5. Change of maximum stresses in the measurement point 2 in time for different stopes

The maximum stresses as a function of time are shown in Fig. 6.

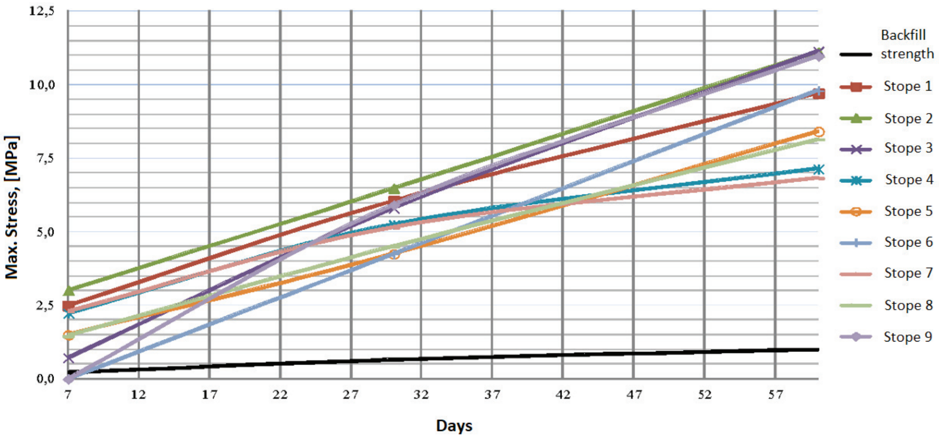

Fig. 6. The maximum stresses depending on the time after backfilling

The starting point is the completion of the filling work for each stope and the time interval of 7–60 days is considered, when the main strength gain of the fill material occurs. As can be concluded from this graph, the highest expected stresses (stope 2) among the maximum is 11.1 MPa. These data make it possible to create a fill mass with known and necessary characteristics in advance, taking into account the strength gain period of the fill mass and changes (redistribution) of rock pressure.

7. CONCLUSIONS FROM NUMERICAL ANALYSIS

After 213 days, the backfill has practically no noticeable strains and the kinetics of rock pressure noticeably slows down. In this model, using in-situ measurements at various points, the maximum stresses and strains are determined, which will subsequently allow predicting: integrity violation of the mass (the formation of man-made fracturing); violation of the waterproof strata; the impact of mining on the earth's surface. Also, this method allows to determine the optimal value of the strength characteristics of the fill mass. This makes it possible to create a fill mass with predetermined specified characteristics, which allows to choose the optimal composition of the backfill mixture when developing a deposit with artificial support of mining area.

8. FINAL REMARKS

Both civil engineering and mining sectors of industry have the potential of waste-free production, which determines the use of intermediate products (industrial waste) in a closed cycle of the main and auxiliary industries. For a harmonious and balanced exploitation of natural resources, it is necessary to carry out technological and technical changes in industrial and mining production, to adjust the direction of investments, to reorient the development vector of scientific and technical research.

It should be taken into account that the use of geotechnology with a backfill in the development of salt deposits, along with the potential for waste-free production, can improve the qualitative and quantitative indicators of extraction and increase the safety of mining operations. Modeling in the FLAC3D program makes it possible to predict changes in the stress–strain behavior of the mined salt mass, assess the possibility of cracks, and as a result, ensure the safety of the waterproof strata, protect the mine from flooding, which will increase the safety of mining operations. The use of numerical modeling allows to select the parameters of the mining technology. Modern methods of numerical modeling allow to predict the possibility and applicability of waste-free technologies, as well as assess the positive combined impact of intermediate products construction and mining industry both on the safety of mining operations and on the environment.

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