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SIMULATION MODELLING OF STRESS FIELD IN THE VICINITY OF THE STOPE OF OREBODY

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ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ ПОЛЯ НАПРУЖЕНЬ НАВКОЛО ВИДОБУВНИХ КАМЕР РУДНИХ ПОКЛАДІВ

Purpose. To evaluate and determine the nature of distribution of stress maximum values in the vicinity of the stope of steeply dipping orebody to optimize further drilling and blasting operations (DBO) applying experimental research and numerical methods.

Methodology. Under laboratory conditions, a few series of experimental research on stress field distribution in the vicinity of the stope model with the use of the developed method of simulation and computer modelling of stress-strain state (SSS) involving the finite element method (FEM).

Results. The experimental and theoretical results of SSS of rock massif are proposed in two schemes of the suggested mining block model in elastoplastic formulation by using FEM. With the use of the developed methods patterns of changes in SSS of rock massif were established in the cross section of the recess chamber which extends along the axis considering the depth of the chamber and the different angles of inclination as well as changes of geomechanical parameter Q, depending on the intensity of the main maximum stress. The dependences of the stress distribution in the model for chamber cross-section along the axis are developed. They showed the formation of units with minimum stress values in the cross section of the central part of the chamber on axis borders on one side of the chamber of the hanging wall, and on the other, the footwall, i.e., in zone of high stress or stress redistribution.

Scientific novelty. The established patterns of distribution and the numerical values of maximum stress in the vicinity of stope of steeply dipping orebody before blasting will allow correcting the process parameters. Taking into account the changes of geomechanical processes in the vicinity of the stope, one can substantiate locations of the drilling room laying, drilling direction of ascending or descending sets of fanholes and the conditions of drilling as well as blasthole charge design, which will increase the efficiency of ore destruction and reduce the level of seismic impact on protected objects of undermined territories.

Practical significance. When breaking rocks and minerals in the stope block of steeply dipping orebody, efficiency of explosive charges increases, specific consumption of explosives and means of initiation decreases, contamination of ore is reduced and performance of the loading and transport vehicles improves.

Keywords: *stress-stain state, the stope, drilling and blasting operations, photoelasticity method, numerical simulation*

Introduction. Despite the development of new technologies of destruction, based on innovative approaches (thermal degradation, the effects of particle fluxes of high-energy, etc.), an explosion is an effective way in the wide application of resource-saving and environmentally friendly methods of preparation of the rock mass in mines. These methods are based on a thorough study of the features of the failure mechanism of strong compound rocks with the gas-dynamic effects of the explosion on them.

One of the ways to improve the blasting techniques involves forecasting and accounting geomechanical processes in the array, namely the stress-strain state, the type of stress, monitoring of physical and mechanical properties.

Geomechanical processes also depend on the structure, mineral composition, spatial orientation of the crystals, the form of a destructible body, the intensity and speed of deformation.

Studies of the effect of a continuous medium preload on the nature of its subsequent dynamic fracture are becoming increasingly important in mining due to the transfer of sewage treatment works in many fields to the depth where the stress state of the rock mass is to be necessarily taken into account.

Analysis of the initial measurement of the stress field of rock mass at different depths showed that the values of the vertical component of the value are close to γH, where H is formation depth and γ is volume weight of the overlying rocks. Then the principal horizontal stress components can be represented as $\alpha\gamma N$, where α is the coefficient of lateral resistance (a positive value).

In many areas, this circumstance is due to the action of horizontal tectonic forces increasing array of elastic energy through the increase of compressive stresses. Conducting drivage and clearing works leads to a significant redistribution of the initial stress field while volume compression is the predominant state of the mechanical state of the rock mass. In these circumstances, the necessary quality of the destruction of rocks at the depth of the development of the growth is achieved by increasing energy costs, that is by increasing the mass of explosives used [1].

Lowering the level of extraction works has particularly negative impact on the conditions of the development of iron ore and uranium deposits in Ukraine, where chamber mining is applied with sub and drifts through alternately block working and filling using consolidating stowing mixture.

One of the promising ways to overcome this situation is to predict failure and to consider regularities of prestressed continuous medium destructed by explosion to develop advanced technologies for the extraction of ore deposits of complex structure, which are iron and uranium deposits in Ukraine. In this context, it is important to consider the fact that under hydrostatic compression of rock volume, the increase in stress degrades the quality of the destruction of rock mass whereas at a certain degree of broken condition, quality of broken rock mass by explosion can be extremely unsatisfactory.

However, the formation of zones with prevailing values of tensile stresses in a continuous frangible medium (thereby reducing the energy for rock destruction) makes it possible to reduce the consumption of explosives and, in addition, to reduce the impact of seismic explosion. Therefore, while developing effective ways of breaking the seismic safety of ore and rock in deep water deposits, including deposits of vein type, studies of the stress field in rock mass in the vicinity of the stope should be considered of high value. They will allow revealing the character of the distribution and calculating numerically the values of stresses in areas of strong compound rocks in various zones of the stope, affecting the ore preparation of steeply dipping deposit. The research areas described above formulate the relevance to solve scientific problems.

Purpose of the work is to evaluate and determine the nature of the distribution of values of maximum principal stress in the vicinity of the stope of steeply dipping orebody applying experimental studies and numerical methods; the results are to be used for further development of rational parameters of drilling and blasting operations.

The study involves conducting two parts of work:

1. Experimental studies of the nature of the stress field when changing the static load in the vicinity of the stope models.
2. Simulation modelling of the stress-strain state of the rock mass in the vicinity of the stope using the finite element method.

Material and results. ***Experimental studies of the nature of the stress field in the vicinity of the stope models.*** For the formation of the character of the stress field in the vicinity of the stope the model used the developed technique of SSS simulation of rock mass, based on the photoelasticity method or fibre-polarization method [2].

The method is based on the ability of transparent materials to acquire the properties of polarized light birefringence under the influence of stresses arising in them. Both sheet glass and bulk organic glass (polymethylmethacrylate) with stable strength, mechanical and optical constants can be referred to optically active materials. In our case, the model sheet organic glass of constant thickness of 0.015 m was used to produce the model. Basic concepts of the methodology have been described in papers by K. S. Ishchenko, A. P. Krukovsky, V. V. Krukovskaya.

Selection and substantiation of the model parameters with the stope are based on considering the condition of wall rocks and ore deposits, technological feasibility and safety of mining operations, as well as parameters of technological equipment, that is hydraulic press test of PSU-125 type. These include technological stroke of the upper press plate and the boundary values of force applied to the models that correspond to the performance of the original stress field of rock mass at depths of 350–450 m. Thus, for example, the East Wing of the Central deposit of uranium ore (GP VostGOK, Kirovograd) with the technological parameters of the chamber mining development with filling and cutting sub or drift, stoping are carried out in the chamber 60–80 m high with cutting sub 12–17 m high, and the width of the chamber sections is 10–18 m. The initial stress field of rock mass represented by uranium containing granite with density $\gamma =$ $= 2.75–2.85$ t/m^3 with an average depth of development equal to $H = 400$ m, taking into account the coefficient of lateral resistance α ($\alpha = 1.3$) will be ~ 13.0–14.0 MPa. Breaking static load for the test patterns to the selected facets of equal size 0.2×0.15 m after preliminary tests did not exceed 20.0 MPa, which corresponds to the initial stress field for the specific conditions of mining operations in the field. For clarity and reliability of the results of experiments, the geometric relationship of the nature and model was accepted at a ratio of 1 : 100.

After substantiation of the geometrical parameters of the rock mass model in the laboratory, a 0.2×0.15 m size model was formed from a sheet of organic glass with a circular saw; using a milling machine, in the center of the model a chamber was cut in the form of a parallelepiped with horizontal floor pillar and bottom m long 0.05 m wide with inclination of 85° and 75°. To study the nature of the stress field and to process the results of the research on the side polished surfaces of the models a square grid with a 0.002 m pitch was drawn with a marking pen .

Methodology of experimental studies involves two series of experiments according to the selected scheme of the rock mass model. In the first series chamber was made at 85° inclination to the horizontal plane, and in the second series it was 75° with regard to the intended changes in the angle of incidence of ore deposit. Experimental studies were carried out in laboratory conditions using proven methods of research of stress-strain state of rock mass models with the help of the developed stand [2]. The scheme of the experimental stand is shown in Fig. 1.

Stand with the equipment included in its configuration (Fig. 1) was calibrated before the experiment while consistency of the stand systems and equipment was checked by testing them on a joint stable performance. Then, between the pressing plates of the press the model prepared was set according to the selected scheme and loaded. On the horizontal surface of the lower press plate, the model was set in such a way that align presumed optical axis centre on one side there was a light source and a polarizer, and on the other side there was an analyser and a digital camera. Since the optically active material is anisotropic in stress state, it allows light waves in mutually perpendicular directions at different speeds.

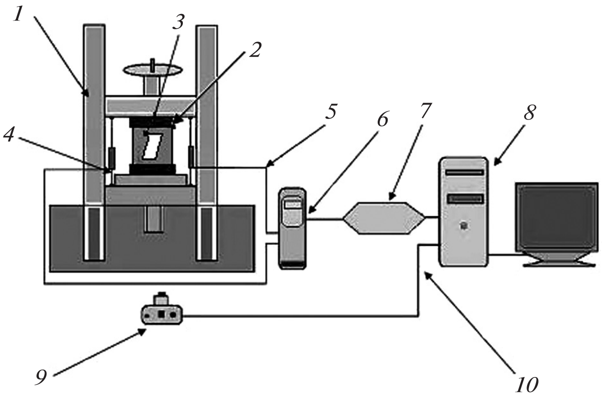


Fig. 1. Scheme of the stand to simulate SSS of rock mass:

1 — the hydraulic press; 2 — the pressure plates of the press; 3 — model; 4 — non-contact magnetic sensors; 5 — connection cable; 6 — digital converter; 7 — the 6 RS-232 interface; 8 — PC system; 9 — digital camera; 10 — USB port

Therefore, when light passes through the model, the so-called path difference of these two rays occur and on the screen analyzer there appear series of bands — isochromes of various colours and intensities. According to the colour of isochrome the intensity of the stress state of the model is evaluated. Each isochrome corresponds to a certain level of the difference between the maximum and minimum principal stress components ($\sigma_1 - \sigma_3$). Fixation of the stress fields was carried out through video recording with an Olympus digital camera with a set step of loading on the model every 2.5 MPa. According to the video recording and simultaneous recording of the operator commands to the system disk of the PC, regarding each stage of loading, the process was framed and recorded using standard video editing program Windows Media Player Classic, while kinograms formation process, which is shown in Fig. 2, was done using the program CorelDRAW X6. The research have shown that under the action of a static compression load of 2.5 MPa, a light coloured field is observed in the models in the vicinity of the chamber, sectioned along the axis both in lying and hanging sides which corresponds to the isochromes of the first order (Fig. 2, *a*, *b*) which characterize the zone with a minimum value of the maximum compressive stress. These pressures have resulted in intensification of the stresses in the corners of the floor pillar and bottom chambers. Further increase in load to 5.0–10.0 MPa resulted in increased area of the zone of reduced stress by 1.5 times within the same borders: isochromes of the first order and the chamber walls for two types of models. The analysis of further testing of models with increasing loads up to 10.0–17.0 MPa

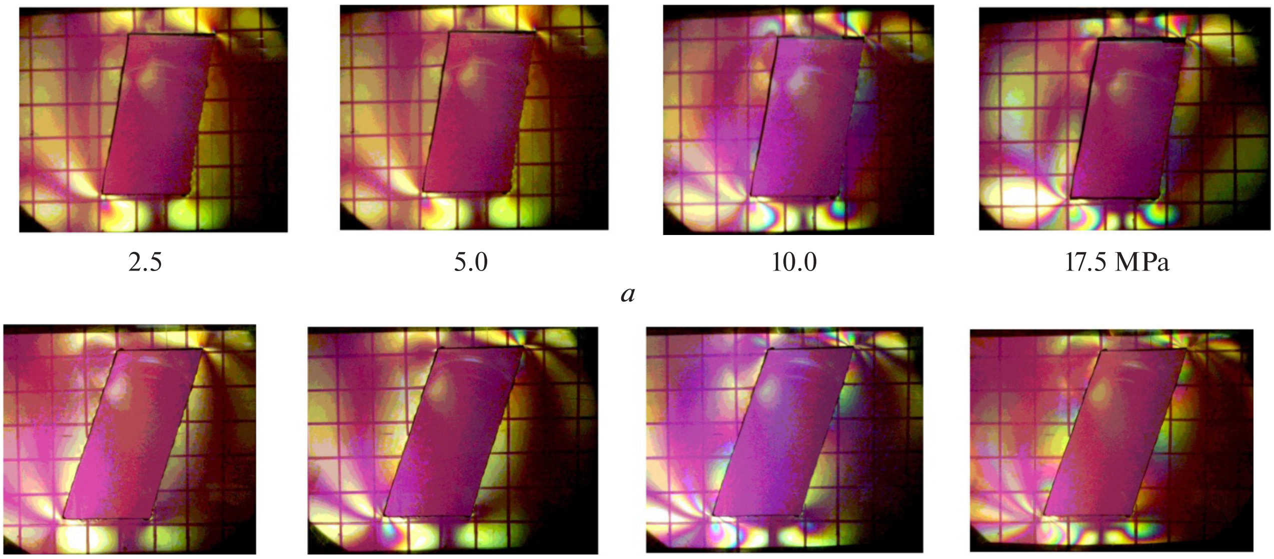


Fig. 2. Photographs of the stress field distribution according to the value of the load applied to the model with a rectangular chamber directed at an angle to the horizontal which is: a — 85°; b — 75°

showed a significant change in the nature of the stress field with the 85° angle of the chamber compared with the 75° angle of inclination. Thus, for the first version of the model (the 85° chamber angle) the area of low voltage decreased, but there appeared areas of stress redistribution and their concentration in the acute angles of the floor pillar and bottom of the chamber.

The changes indicate an increase in stress in the model in the vicinity of the chamber when the loading increases (the appearance of concentric isochrome of higher orders). The zone of elevated stress, limited by isochromes for the studied types of models, differs only in the area formed by this isochrome. The results of studies prove that the rational place of laying the drilling workings of mining in the chamber can be carried out according to the following guidelines:

- from the top of the chamber or the next level of the upper border of the floor or sublevel at a distance equal to at least the height of a floor or sublevel $h_{fl} \geq 12–17$ m, where h_{fl} is the floor height, in the area of low-stress states near the camera both in hanging loop, and in the footwall;
- horizontally at a distance from the proposed boundary of the chamber of both hanging and footwall equal to 1/2 $\ell_{w.c}$ or a chamber section 1/2 ($\ell_{w.c.s}$) where $\ell_{w.c}$ is the width of the chamber (12–18), m; $\ell_{w.c.s}$ is the width of the chamber sections (9–12) m, which corresponds to zones of redistribution or low-stresses near the central section of the chamber as well as at the chamber bottom.

Stress state simulation of the rock mass in the vicinity of the mining chamber using the finite element method (FEM). As it was mentioned above, SSS simulation of rock mass, allows a scientific approach to the selection and substantiation of the technological parameters of the systems development: places of laying the drilling workings, drilling a set of fanholes, forming of blasthole explosive charges in their rational structures. This approach allows us to implement modern management methods for explosive destruction of hard rock, providing high-quality crushing of the rock mass and seismic safety complex of buildings and structures of the surface.

To confirm the adequacy of the selected physical SSS simulation model of rock mass, computer simulation was conducted with solving the SSS of the rock mass in the vicinity of the stope in the elastic-plastic formulation using numerical methods – the finite element method (FEM) as a method of movement. The algorithm for solving the problem involves the following sequence of calculation by the finite element method:

- formation of the model parameters, splitting the model into finite elements and the appointment of nodes in which displacement occurs;
- construction of the stiffness matrix and load vector of finite elements;
- drawing up a system of algebraic equations and their solutions;
- definition of the stress-strain state according to the model displacement.

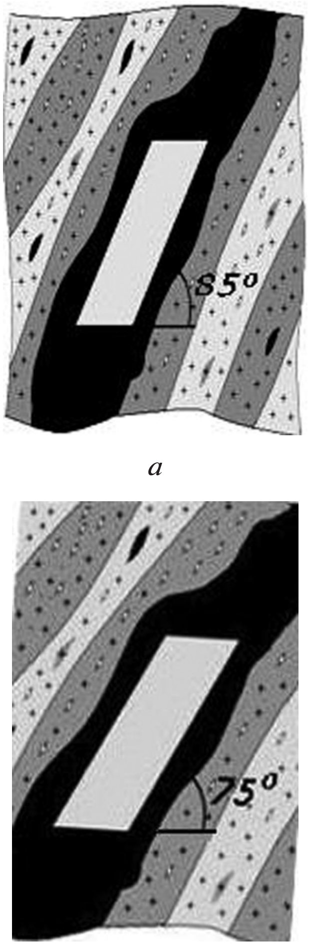
Let us consider the model schemes of the rock mass in the vicinity of the stope for the numerical solution of the problem of SSS changes: *a* – a model of the rock mass including stope in orebody with an angle of incidence equal to 85°; *b* – a model of the rock mass including stope in orebody with an angle of incidence equal to 75°. The parameters and geometrical dimensions of the model correspond to the selected physical model for studying SSS of rock mass described above. The calculation model is shown in Fig. 3.

The evaluation of SSS is conducted according to the geotechnical parameter characterizing the different components of the stress field,

$$Q = \frac{\sigma_1 - \sigma_3}{\gamma H},$$

where σ_1, σ_3 are the maximum and minimum principal stress tensor components; γ is the volume weight of the overlying rocks; H is formation depth.

As a result of the calculation, the record of distribution of values of the geomechanical parameter *Q* was obtained for the models under analysis at the maximum load which are shown in Fig. 4.



a

b

Fig. 3. Calculation model of SSS in the vicinity of "orebody – stope" system with an angle of incidence: a – 85°; b – 75°

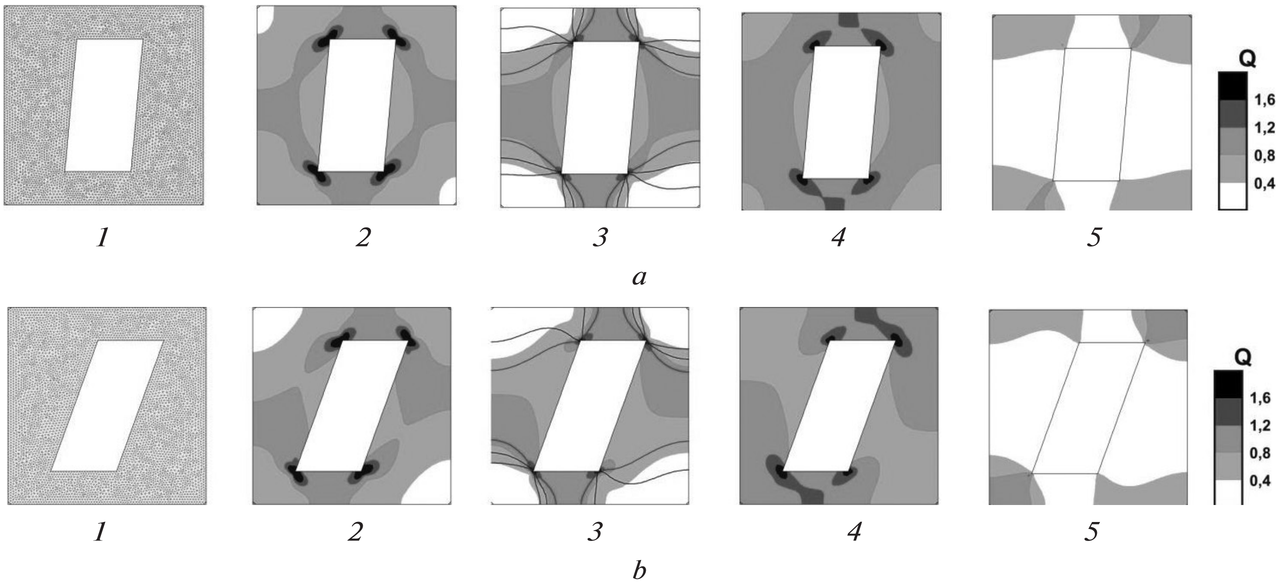
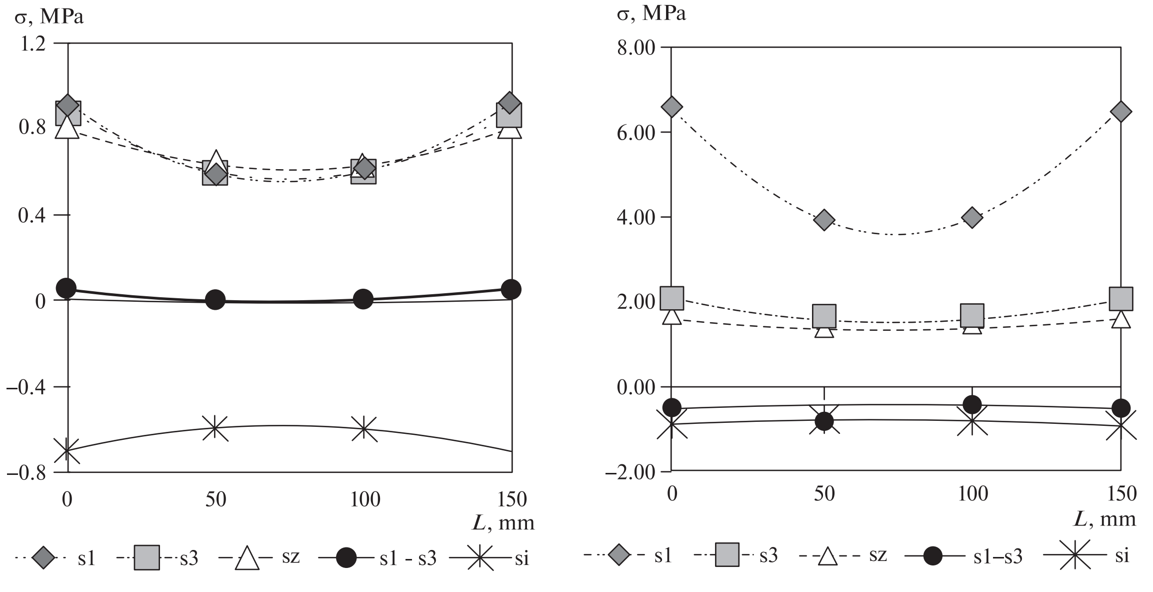


Fig. 4. Distribution of geomechanical parameter Q values of rock mass model in the vicinity of the "orebody—stope" system with an angle of incidence:

a — 85°; b —75°; 1 — finite element mesh; 2 — stress intensity; 3 — difference between the principal stresses and minimum; 4 — σ_{max} — maximum principal stresses; 5 — σ_{min} — minimal principal stresses

Fig. 4, *a*, shows that in the vicinity of the chamber at an angle of 85° of the model, high stress zone develops on the surface of the floor pillar, cell floor and in the corners ($0.8 < Q < 1.2$). The most unloaded zone is set for the model with angle 75° (Fig. 4, *b*) in the centre of the cross section along the axis ($Q = 0.4$–0.8), both in a footwall and in the hanging wall, but with limited by the chamber walls on one side and by higher stress field ($Q = 0.8$–1.2) on the other.

The intensity of the main maximum stress for two selected models is similar both for the floor pillar surface and at the bottom of the chamber. Furthermore, by increasing the load the maximum values of the principal stresses are shifted to the floor pillar and to the bottom of the chamber with the area changing and followed by redistribution within the cross-section and along the axis. Fig. 5 shows the measurement of relative maximum principal stress tensor components $\sigma_1/\gamma H$ in



a

b

Fig. 5. Changes in the relative maximum principal stress tensor components $\sigma_1/\gamma N$ along the axis of the stope of steeply dipping orebody at an angle:

a — 85°; b — 75°; S1 — σ_1 — maximum principal stresses; S3 — σ_3 minimal principal stresses; S1–S3 — σ_1–σ_3 — difference between maximum and minimum principal stresses; SZ — σ_z — stresses perpendicular to the plane of model; Si — σ_i — stress intensity the model of steeply dipping orebody passing through the centre and along the axis of the stope.

Dependency analysis showed (Fig. 5, *a*), around the chamber at the angle of 85° within the boundaries of the model, the maximum principal stress concentration is $\sigma_1 = 6.9$ MPa, while $\sigma_1 = 4.0$ MPa on the surface of the chamber at distance of 0.05 m.

These values do not change on the opposite wall of the chamber in the footwall as well. For the given model the behaviour of the minimum principal stress σ_3 and the stress perpendicular to the plane of the model σ_z is almost indistinguishable. Stress values for the model with angle of 75° (Fig. 5, *b*) are quite different. The behaviour of maximum σ_1 and minimum principal stress σ_3, the stress perpendicular to the plane of the model σ_z are similar in characteristics and are in the range of 0.6–0.8 MPa, which are significantly lower (by 6–8 times) for the model with the angle of 85°. Moreover, the difference between the maximum and minimum principal stresses $\sigma_1 - \sigma_3$ does not change significantly ($\sigma_1 - \sigma_3 = 0.1$ MPa), and the intensity of the stresses σ_i on this grid coordinate changes in a parabolic dependence. The intensity of the calculated stresses σ_i for the model under analysis proves the prevalence of stress redistribution zones, zones of low stress and dynamics of growth of tensile stresses that contribute to increasing efficiency of breaking strong tense rock, explosion efficiency factor and reduce the cost of drilling and blasting work.

Conclusions. According to the results of simulation and numerical solutions of the approved methods of physical modelling and the finite element method, carried out for several models of the "rock mass – stope" system, we established the following:

1. With load on the model changing within the range of 2.5–17.5 MPa for two variants of the chamber at angles of 85° and 75°, the stress field at early stages remains almost identical. With increasing load (10.0–17.5 MPa) there appear zones of increased intensity and redistribution of stresses shifting to acute corners both in the floor pillar and the bottom of the chamber which corresponds to an increased concentration of the isochrome of higher orders.

2. Experimental and numerical calculations of stresses in the rock mass in the vicinity of the stope substantiated the efficient location of the drilling workings with the following coordinates:

- from the top of the chamber or mark from the top border of the following floor or sublevel at a distance equal to at least the height of a floor or sublevel $h_{fl} \ge 12$–17 m, where h_{fl} is floor height m, in the low stress area near the chamber both in hanging loop and in the footwall;

- horizontally at a distance from the assumed boundary of the chamber of the hanging wall equal to $1/2\ell_{w.c}$ or the chamber section 1/2 ($\ell_{w.c.s}$) where $\ell_{w.c}$ is the width of the chamber (12–18), m; $\ell_{w.c.s}$ is the width of the chamber sections (9–12) m, which corresponds to zones of redistribution or low stresses near the centre of the chamber cross-section.

3. With increase in the depth of excavation of ore deposits in the stope which corresponds to increased loads applied to the model, drilling blast holes should not extend beyond the boundaries of the proposed area of maximum principal stress ($Q = 0.8$–1.2) or in the area of low stress ($Q = 0.4$–0.8) for the entire height of the stope, except for the floor pillar and bottom chamber when the boundary height of the floor or sublevel is selected from the conditions of stability of the floor pillar, but no more than $hf_l \le 12$–17 m;

4. For models with a chamber angle of 75° difference between the maximum and minimal principal stresses $\sigma_1 - \sigma_3$ is distributed within the positive area ($\sigma_1 - \sigma_3 = 0.1$ MPa), while the intensity of stresses σ_i on this grid coordinate changes in a parabolic dependence which indicates the prevalence of stress redistribution zones, zones of increased stress and dynamics of growth of compressive stresses over tensile stresses within the model under analysis; these contribute to increasing efficiency of breaking strong tense rock, explosion efficiency factor and reduce the seismic effects of blasting on undermined territories.

5. Experimental and numerical stress calculation shows good convergence of data and the adequacy of the model chosen to solve the problems.

6. The results of the research will be recommended for their testing under industrial conditions of deep mines iron ore and uranium deposits in Ukraine.

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Мета. Оцінити та визначити характер розподілу значень максимальних головних напруг навколо камери блоку видобутку крутопадаючого рудного покладу для подальшої розробки раціональних параметрів буропідривних робіт (БПР).

Методика. Проведено декілька серій експериментальних досліджень у лабораторних умовах з вивчення характеру розподілу поля напруг навколо камери моделі блоку видобутку з використанням розробленого способу імітаційного та комп'ютерного моделювання напружено-деформованого стану (НДС) масиву з використанням методу кінцевих елементів (МКЕ).

Результати. Представлені експериментальні й теоретичні дані НДС масиву за двома схемами запропонованої моделі блоку видобутку у пружнопластичній постановці. З використанням розроблених методів встановлені закономірності зміни НДС масиву в перетині камери, що проходить уздовж осі камери з урахуванням глибини її закладання та різних кутів нахилу, зміни геомеханічного параметра Q у залежності від інтенсивності головних максимальних напруг. Побудовані залежності зміни тензора головних напруг перетину камери уздовж її осі в моделі. Залежності показали, що в перетині центральної частини камери по її осі, як з боку камери висячого боку, так і з боку лежачого боку покладу, формуються ділянки з мінімальними значеннями напруг за рахунок їх перерозподілу в зонах підвищених напруг.

Наукова новизна. Встановлені закономірності розподілу та чисельні значення максимальних напруг поблизу камери блоку видобутку крутопадаючого рудного покладу до ведення БПР дозволять коректувати їх технологічні параметри. З урахуванням змін геомеханічих процесів навколо камери блоку видобутку можна обґрунтувати місця закладення бурових виробок, напрям буріння висхідних або низхідних комплектів віялових свердловин і умови їх буріння, раціональні конструкції свердловинних зарядів вибухових речовин (ВР) для цих умов, що підвищить ефективність відбою корисних копалин та знизить рівень сейсмічної дії на об'єкти, що охороняються територій, що підробляються.

Практична значимість. При відбійці гірських порід і корисної копалини у блоці видобутку крутопадаючого рудного покладу підвищується коефіцієнт корисної дії вибуху свердловинних зарядів ВР, знижується питома витрата ВР і засобів підривання, зменшується розубожування корисної копалини та покращуються показники роботи вантажних і транспортних засобів.

Ключові слова: *напружений стан, видобувний блок, камера, буропідривний спосіб відбійки, метод фотопружності, чисельне моделювання*

Цель. Оценить и определить характер распределения значений максимальных главных напряжений вокруг камеры добычного блока крутопадающей рудной залежи для последующей разработки рациональных параметров буровзрывных работ (БВР).

Методика. Проведено несколько серий экспериментальных исследований в лабораторных условиях по изучению характера распределения поля напряжений вокруг камеры модели добычного блока с использованием разработанного способа имитационного и компьютерного моделирования напряженно-деформированного состояния (НДС) массива с использованием метода конечных элементов (МКЭ).

Результаты. Представлены экспериментальные и теоретические данные НДС массива по двум схемам предложенной модели добычного блока в упругопластической постановке. С использованием разработанных методов установлены закономерности изменения НДС массива в сечении камеры, проходящей вдоль оси камеры с учетом глубины ее заложения и различных углов наклона, изменения геомеханического параметра Q в зависимости от интенсивности главных максимальных напряжений. Построены зависимости изменения тензора главных напряжений сечению камеры вдоль ее оси в модели. Зависимости показали, что в сечении центральной части камеры по ее оси, как со стороны камеры висячего бока, так и со стороны лежачего бока залежи, формируются участки с минимальными значениями напряжений за счет их перераспределения в зонах повышенных напряжений.

Научная новизна. Установленные закономерности распределения и численные значения максимальных напряжений вблизи камеры добычного блока крутопадающей рудной залежи до ведения БВР позволят корректировать их технологические параметры. С учетом изменений геомеханических процессов вокруг камеры добычного блока можно обосновать места заложения буровых выработок, направление бурения восходящих или нисходящих комплектов веерных скважин и условия их бурения, рациональные конструкции скважинных зарядов взрывчатых веществ (ВВ) для этих условий, что повысит эффективность отбойки полезного ископаемого и снизит уровень сейсмического воздействия на охраняемые объекты подрабатываемых территорий.

Практическая значимость. При отбойке горных пород и полезного ископаемого в добычном блоке крутопадающей рудной залежи повышается коэффициент полезного действия взрыва скважинных зарядов ВВ, снижается удельный расход ВВ и средств взрывания, уменьшается разубоживание полезного ископаемого и улучшаются показатели работы погрузочных и транспортных средств.

Ключевые слова: *напряженное состояние, добычной блок, камера, буровзрывной способ отбойки, метод фотоупругости, численное моделирование*

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