Investigation into near-contour stresses in stoping with backfilling by the polarization-optical method

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Abstract. When mining deposits with room-and-pillar methods with backfilling, available hanging wall rocks and ores of medium or low stability can cause hanging wall rock collapses into stoping areas, thus causing escalation of ore dilution with waste rocks. The research work is aimed at determining areas of maximum stresses and their quantitative characteristics which can cause collapses of hanging wall rocks in the mined-out stope area and developing technological solutions to reduce concentration of stresses. Options of mining stopes located on the hanging wall of the deposit are investigated on polarization-optical models. According to the results of studying polarization-optical models with different designs of stope chains, there are obtained stress fields for each model in the zone of stope influence. The research reveals that when using a stoping method with partial processing of hanging wall rocks in the contact plane with the country rocks, the maximum stresses are much higher than in case of the arched form of the stoping area. On the basis of the obtained research results, it is recommended to carry out chambers with the formation of a vaulted shape of the roof from the hanging side in order to reduce the clogging of the ore.

1. Introduction

When performing stoping operations, there is a tendency of increasing the robbed-out space in rooms resulting in changes in the volumetric stress state of the rock massif adjacent to the stoping area [1–3]. This consequently initiates geomechanical processes that cause strains of the rock massif and the stope contour collapse. The nature of geomechanical processes occurring in the rock massif adjacent to the robbed-out space is determined by mining and geological conditions [4]. With increased mining depths, rock pressure naturally increases and so do stresses in the near-contour massif [5–7] in room-and-pillar mining. In conditions of mining deep levels of Pivdenno-Bilozirskyi deposit, poor stability and low strength of the hanging wall rocks are the main and determining factors causing disturbances of stoping area contours [8] in mining operations [4]. Low and extremely low stability of ores and country rocks contributes to lost stability of stoping area contours.
2. Purpose
The research aims to develop recommendations on parameters, forms and procedures for stoping, including search for possible partial changes in the shape of stopes, and procedures of their mining under increased stresses in the near-contour massif when conducting stoping operations by the room-and-pillar method with backfilling.

3. Methodology
To research into stresses in the near-contour massif when stoping, a polarization-optical method with transparent models made of optically sensitive materials (photoelasticity) [9, 10] is used to obtain data on distribution and values of stresses in the rock massif with mine workings of various purposes and sizes.

The polarization-optical method of studying stresses is based on properties of most transparent isotropic materials to acquire the ability of double radiation under the influence of stresses (or strains). The value of double refraction associated with that of stresses can be measured optically when the model is transilluminated with polarized light. Polarization and double refraction are optical phenomena underlying the polarization-optical method. When conducting research by the polarization-optical method for obtaining flat-polarized light, so-called polarizers are used that permit light oscillations only in one plane – in the plane of oscillations.

As is known from the theory of elasticity, the stress-strain state of the solid’s point is characterized by six components of stresses: \( \sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz} \) or six components of strains: \( \varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{xz}, \gamma_{yz} \) [11].

The method of photoelasticity is based on laws of the elasticity theory which sate that the relationship between stresses and strains is subject to the Hooke law and for triaxial stress is expressed in the form of:

\[
\begin{align*}
\varepsilon_x &= \frac{1}{E}[\sigma_x - \mu(\sigma_y + \sigma_z)] \\
\varepsilon_y &= \frac{1}{E}[\sigma_y - \mu(\sigma_x + \sigma_z)] \\
\varepsilon_z &= \frac{1}{E}[\sigma_z - \mu(\sigma_x + \sigma_y)] \\
\gamma_{xy} &= \frac{1}{2G}\tau_{xy}; \gamma_{yz} = \frac{1}{2G}\tau_{yz} \\
\gamma_{xz} &= \frac{1}{2G}\tau_{xz}; G = \frac{E}{2(1 + \mu)}
\end{align*}
\]

where \( \sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{xz}, \tau_{yz} \) are stress components,
\( \varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{xz}, \gamma_{yz} \) are strain components,
\( \mu \) is the Poisson ratio,
\( E \) is the elasticity modus,
\( G \) is a the shear modus.

Many problems of the elasticity theory can be reduced to solving a flat problem eliminating significant difficulties of manufacturing a model and, especially, of mathematical processing of
test results. Then, the Hooke law is written in the form of:

\[
\begin{align*}
\varepsilon_x &= \frac{1}{E}[\sigma_x - \mu\sigma_y] \\
\varepsilon_y &= \frac{1}{E}[\sigma_y - \mu\sigma_x] \\
\gamma_{xy} &= \frac{1}{2G}\tau_{xy}
\end{align*}
\] (2)

To match the modelled processes and the prototype ones when manufacturing a model, it is necessary to follow a number of similarity criteria [12].

To bring the geometrical parameters of the model in line with the prototype ones, the geometric scale of modelling is taken:

\[
\alpha = \frac{l_n}{l_m} = \text{const}
\] (3)

where \(l_n, l_m\) are the length of any similar segments in the prototype and the model respectively.

For concentrated loads, the force scale is accepted:

\[
\beta = \frac{P_n}{P_m} = \text{const}
\] (4)

where \(P_n, P_m\) are the forces applied to similar points of the prototype and the model.

Then the similarity scale of uniformly distributed loads or stresses \(\delta\) will be associated with the force scale \(\beta\) through the geometric scale \(\alpha\):

\[
\delta = \frac{\sigma_n}{\sigma_m} = \frac{\beta}{\alpha^2} = \text{const}
\] (5)

where \(\sigma_n, \sigma_m\) are the stresses applied to similar points of the prototype and the model.

Poisson ratios of materials of the prototype \(\mu_n\) and the model \(\mu_m\) as dimensionless quantities should be equal

\[
\mu_n = \mu_m
\] (6)

Fulfillment of similarity conditions (3)-(6) is sufficient for the studied stresses, shears and strains in the model to meet the same prototype parameters.

The polarization-optical method of studying stresses on transparent models of optically sensitive materials makes it possible to obtain distribution and values of stresses in the rock massif with different geometric parameters of the stope. To do this, the model gradually reproduces stoping stages and at each stage isochromatic (lines of the same colour, characterizing stress differences) and isoclinic (lines with the same angle of main stresses) images are taken. An isostatic image is built based on the isoclinic image. According to the obtained isochromatic, isoclinic and isostatic images, the values of stresses along straight lines parallel to the coordinate axes (x and y) are calculated.

To study the stress state of the rock massif on polarization-optical models, the latter are made of low-modulus materials that operate under their own weight. The optically sensitive material – igdantine – is used for manufacturing polarization-optical models.
4. Research results

To manufacture the models, the optically sensitive material – igdantine – of the following composition is adopted: gelatin - 25%, glycerin - 30%, water - 45%, as it is the most suitable for modelling the desired processes providing sufficient information about the stress state of the rock massif in the proximity of the robbed-out stoping area of various geometry.

The igdantine model is made according to the generally accepted methods [10] as follows. According to parameters of a cassette for manufacturing the model, the required amount of igdantine is prepared. To do this, the required amount of water is poured into the calculated portion of gelatin stirring slowly. The mixture swells for 5-8 hours and is mixed thoroughly with glycerin added. The resulting mixture is aged for 20-24 hours, after which it is thoroughly mixed again and heated for 5 hours to the temperature of 80-90°C in a water bath. When heating, the mixture is slowly stirred three-four times to remove the foam layer. The molten mixture is aged at this temperature for 1.0-2.0 hours. The resulting solution is filtered and poured into the specially prepared split mould (cassette) with transparent walls. The cassette with the filled molten mixture is placed into the bath with water heated to 70-80°C in order to slowly cool and remove bubbles. 10-15 hours after cooling the model to the ambient temperature (18-20°C), the mould (cassette) is split in a horizontal position and the model is carefully separated from the walls of the cassette. The surface of the model is coated with oil (castor oil) to reduce friction against the walls of the cassette.

When manufacturing, building and testing the model, it is necessary to ensure compliance with determining criteria of similarity, observe geometric similarities of the model and the prototype as well as boundary conditions.

Based on the model dimensions determined by the size of the mould (cassette) and considering boundary conditions and trying to achieve the maximum possible size of the studied objects (robbed-out areas of stopes and the adjacent rock massif) the geometric scale $\alpha = 1:1000$ is used when modelling.

At the first stage of testing in the rock massif, the models form the position of stoping operations prior to testing the studied objects, i.e. mining and backfilling are modelled in the upper levels.

Thus, the model is ready for modelling stoping operations in the research area.

Next, stoping is modelled according to the scheme in figure 1, i.e. for stoping conditions of partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall as shown in figure 2 – for breaking stope reserves so that in the place of the robbed-out stoping area exit in contact with the hanging wall rocks, an arched form of the robbed-out area is formed.

After cutting the model in the massif according to the scale of the stoping area, the model is placed in a polarizer for testing through transilluminating by polarized rays. During the tests, isoclinic images and isochromatic images are photographed at different angles of the polarizer. The performed researches of the manufactured and tested models made of optically sensitive material during transillumination by polarized rays allow obtaining data on distribution and values of stresses in the rock massif adjacent to the mined-out stope. The research is performed in accordance with generally accepted classical methods [9, 10]. The testing results of models are processed after testing each model.

The procedure for processing and obtaining the testing results of each of the models is performed in the following sequence: first, isoclines at different angles of the polarizer are built. When building isoclinic lines, the following properties of isoclines should be observed:

1. Only one isocline of a certain parameter passes through each stress point of the model. Exceptions are isotropic points.

2. Isoclines of all parameters run through isotropic points. The position of isotropic points is determined by the isochromatic image in which isotropic points are represented by dark zones.
3. Isoclines of all parameters converge at the point of load application in the same way as at the isotropic point. This phenomenon should be observed in a completely acute incision. In fact, the incision has a curvature of a small radius. Therefore, isoclines of different parameters will cross the curved zone of the incision. With a small radius of the curvature, it seems that in sharp incisions, isoclines converge at one point. Isotropic points at which the isocline parameter (determined by synchronous rotation of the polarizer and the analyzer corresponding to the inclination angle of one of the main stresses) increases counterclockwise by traversing, are called positive isotropic points. If the isocline parameter increases when traversed clockwise, the isotropic point is called negative.

Figure 1. Modelling of stoping with partial undermining of the hanging wall rocks in the plane of contact with the country rocks of the hanging wall.

4. The parameter of the isocline that goes to the free contour is determined by the direction of the tangent at this point of the contour. Since there is only one main stress on the free contour directed tangentially to the contour, the sections of the rectilinear contour are isoclines of constant parameters.

5. The isocline field determines the direction of the main stresses at all points of the model and is used to build trajectories of main stresses (isostatic lines).

According to the described method, isoclines are built by rotating the polarizer and the analyzer every 10°: i.e. isoclines 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70° and 80° for each model. According to the general isoclinic image, the isostatic line image for each model is graphically built. Isostatic lines, or trajectories of main stresses, are lines tangents to which coincide with the direction of one of the main normal stresses at each point. Since main stresses at each point are mutually perpendicular, trajectories of the main stresses form a system of orthogonal curves.

After building isoclines by auxiliary polarization quarter-wave plates, an isochromatic image is photographed. According to the isochromatic image, in accordance with the results of calibration.
Figure 2. Modelling stoping with breaking reserves so that at the stoping area exit in contact with the hanging wall rocks an arched stoping area is formed.

of the models, images of stress differences for each model are built.

According to the combined image of isoclines and stress differences and the isostatic image, the differences of the main stresses $\sigma_1 - \sigma_2$ and the angles of inclination of the maximum main stresses $\theta$ are determined.

Components $\sigma_x$ and $\sigma_y$ are determined by equations according to the methods [9,10]:

$$\sigma_x = \sigma_{x0} - \int_{x_0}^{x} \frac{\Delta \tau_{xy}}{\Delta y} dx$$

$$\sigma_y = \sigma_{y0} - \int_{y_0}^{y} \frac{\Delta \tau_{xy}}{\Delta x} dx + \int_{y_0}^{y} \gamma dy$$

These equations are solved approximately by graph-analytical integration by the trapezoidal method [9,10]:

$$\sigma_{xn} = \sigma_{x0} - \sum_{i=1}^{n} (\Delta \tau_{xy})_{cpi} \frac{\Delta x}{\Delta y}$$

$$\sigma_{yn} = \sigma_{y0} - \sum_{i=1}^{k} (\Delta \tau_{xy})_{cpi} \frac{\Delta y}{\Delta x} + \gamma \sum_{i=1}^{k} \Delta y_i$$

where $\sigma_{x0}$, $\sigma_{y0}$ are known values of $\sigma_x$, $\sigma_y$ in the initial point (usually within the unmined massif).

$$\Delta \tau_{xy} = \tau_{xy2} - \tau_{xy1},$$

1 is the auxiliary line number with algebraically smaller ordinate;
3 is the auxiliary line number with algebraically greater ordinate.

\[ (\Delta \tau_{xy})_{cp} = \frac{\Delta \tau_{xyi} + \Delta \tau_{xyi+1}}{2} \]  \hspace{1cm} (12)

If \( \sigma_1 > 0 \) and \( \sigma_2 > 0 \), \( \sigma_1 = \sigma_{\text{max}} \), while \( \sigma_2 = \sigma_{\text{min}} \). If \( \sigma_1 < 0 \) and \( \sigma_2 < 0 \), \( \sigma_1 = \sigma_{\text{min}} \), while \( \sigma_2 = \sigma_{\text{max}} \). If the stress has different symbols and \( |\sigma_1| > |\sigma_2| \), \( \sigma_1 = \sigma_{\text{max}} \), \( \sigma_2 = \sigma_{\text{min}} \) and vice versa. If calculations are conducted along the axis \( x \), after calculating \( \sigma_{xi} \) by [9], \( \sigma_{yi} \) is calculated by the formula [10] :

\[ \sigma_{yi} = \sigma_{xi} - (\sigma_1 - \sigma_2)\cos2\theta, \text{if} |\theta| < 45^0 \]  \hspace{1cm} (13)

\[ \sigma_{yi} = \sigma_{xi} + (\sigma_1 - \sigma_2)\cos2\theta, \text{if} |\theta| > 45^0 \]  \hspace{1cm} (14)

If calculations are performed along the axis \( Y \), after calculating \( \sigma_{yi} \) by (9), \( \sigma_{xi} \) is calculated by the formula [11] :

\[ \sigma_{xi} = \sigma_{yi} + (\sigma_1 - \sigma_2)\cos2\theta, \text{if} |\theta| < 45^0 \]  \hspace{1cm} (15)

\[ \sigma_{xi} = \sigma_{yi} - (\sigma_1 - \sigma_2)\cos2\theta, \text{if} |\theta| > 45^0 \]  \hspace{1cm} (16)

The value of tangential stress is determined by the formula:

\[ \tau_{xy} = \frac{\sigma_1 - \sigma_2}{2}\sin2\theta \]  \hspace{1cm} (17)

where \( \theta \) is the angle between the positive direction of the axis \( x \) and the direction \( \sigma_1 \);

\( \sigma_1 - \sigma_2 \) is algebraically greater and algebraically less main normal stresses

Then, \( \sigma_1 \) and \( \sigma_2 \) are calculated as follows [9] :

\[ \sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \tau_{\text{max}}, \]  \hspace{1cm} (18)

\[ \sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \tau_{\text{max}}, \]  \hspace{1cm} (19)

where \( \tau_{\text{max}} = \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2} \)

Based on the calculation results, there are curves of stress concentration factors built for each model in the area of stope influence as they move away from the contours of the robbed-out stoping area towards the hanging and footwalls (figure 2,3).

The results of the tests and researches show that when conducting stoping operations with partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall, maximum stress concentration factors are observed in the upper parts of the hanging walls and footwalls of the stope in the place of their transition into the crown and reach \( 9\gamma_H \) (figure 3). In the point of transition of the inclined exposure of the hanging wall rocks to the vertical wall of the stope from the side of the hanging wall, the stress concentration factor is \( 1.8\gamma_N \) (figure 3). When conducting stoping operations with breaking stope reserves so that at the stoping area exit in contact with the hanging wall rocks the arched form of the robbed-out space is formed, the maximum stress concentration is observed in the upper part of the stope wall from the hanging wall side where it is transformed into the crown and reaches \( 1.6\gamma_H \) (figure 4), while in the upper part of the stope from the hanging wall side in the middle of the arched crown, the stress concentration factor is \( 1.1\gamma_H \) (figure 4).

In the mid-height of the vertical stope wall from the hanging wall side near the stoping area contour, the stress concentration factor reaches \( 1.2\gamma_H \) in both models (figure 3,4).
Figure 3. Curves of coefficients of maximum stress concentrations in the rock massif after stoping in the hanging wall of the deposit with partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall.

Figure 4. Curves of coefficients of maximum stress concentrations in the rock massif after stoping in the hanging wall of the deposit so that at the stoping area exit in contact with the rocks of the hanging wall an arched stoping area is formed.

5. Conclusion
The research indicates that when stoping in the hanging wall of the deposit with partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall, stresses reach from $1.8 \gamma N$ at the transition point of the inclined exposure of the hanging
wall rocks into the vertical stope wall from the hanging wall side to $1.9\gamma H$ at the transition of the inclined plane of the exposed country rocks of the hanging wall in the stope crown. With an arched form of the robbed-out stoping area in contact with the hanging wall rocks in the middle of the arched crown, stresses reach $1.1\gamma H$ which is much less than at partial undermining of the hanging wall rocks in the plane of contact with country rocks of the hanging wall with stresses reaching from $1.8\gamma H$ to $1.9\gamma H$.

Thus, the results of the research enable stating that with hanging wall rocks of medium and low stability, it is expedient to form an arched stope in contact with the exposure of hanging wall rock in order to prevent collapses of the hanging wall rocks into the robbed-out stoping area which can cause greater ore dilution.

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