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Determining modern stress field when mining ore deposits

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Abstract

Introduction. *The article describes a method of modern stress field determination in a rock mass when ore deposits are mined and a circular hole opens up on the earth's surface. This method makes it possible to determine the values of the principal normal stresses in the upper part of the rock mass using modern high-precision electron-optical devices and global positioning systems for observing horizontal shifts of surveying reference network points laid on the earth's surface in the smooth shear zone.*

Formulation of the problem. *When mining ore deposits by the underground method, safe condition of underground mine workings, buildings and structures on the earth's surface is a major issue. To solve this geomechanical problem, modern stress state of the rock mass should be determined. It is suggested that the planned shifts of surveying reference network points and state geodetic network (SGN) points located in the smooth shear zone when a circular hole opens up on the earth's surface should be used to determine the value and direction of principal normal tectonic stresses acting in the horizontal plane.*

Research aim *is to develop a mathematical framework determining modern principal stresses acting in the horizontal plane when caved area outcrops.*

Research objective *is to justify the possibility of using planned shifts of surveying reference network points and SGN points, measured with modern electron-optical devices and global positioning systems (GLONASS and GPS) in the calculations of the rock mass stress state.*

Methods of research. *When determining modern principal tectonic stresses acting in a horizontal plane, the solution of the plane elasticity problem is used to develop a mathematical framework.*

Scope of results. *This method is useful when determining the stress state of a rock mass at large bases when mining ore deposits.*

Results. *The obtained analytic expressions allow determining modern tectonic stresses and their direction in the horizontal plane when a circular hole opens up on the earth's surface. Horizontal shifts of surveying reference network points and SGN points are used to determine the stresses.*

Keywords: *principal normal stresses; smooth shear zone; caving zone; horizontal deformations; stress-strain state; rock mass; hole; horizontal shifts; hole radius; radius vector.*

Introduction. According to the Russian Federation Federal Law "On the Industrial Safety of Hazardous Production Facilities", mining enterprises that develop mineral deposits by the underground method are hazardous production facilities where special requirements must be met in relation to occupational health and safety connected with the stability of underground workings in the course of mining and the protection of surface buildings and structures.

Ore deposits mining method with roof strata caving is accompanied by the caved area outcrop, and the shape of the area can be reasonably well approximated by a circle or an ellipse (plan dimensions are hundreds of meters, both along the strike and down the dip of the ore bodies) [1].

When elaborating actions on buildings, structures and natural features protection from underground mining, it is important to know the values of the horizontal shifts of the earth's surface, which depend on the stress state of the rock mass, and be able to calculate them. The caved zone size growth in the course of mining activates rock mass shear resulting in the development of horizontal deformations on the earth's surface. The direction and values of horizontal deformations in the smooth shear zone depend on the caved area shape and size, rock mass physical and mechanical properties, and the stress-strain state (SSS) [1–6].

Papers [3–6] use the results of instrumental mine surveying observations along profile lines laid on the earth's surface before the caved area outcrop to determine the principal normal stresses acting in a rock mass in the course of iron ore deposit development. To determine the value and direction of horizontal tectonic principal normal stresses, horizontal deformations of 20–100 m profile line intervals were used. Survey observations of the earth's surface shear were carried out in accordance with the instruction for rock and earth's surface shear monitoring in the course of underground mining of ore deposits. Absolute horizontal deformations of intervals were measured with a tape measure with an accuracy of 1 : 20,000. Measurement of horizontal deformations with an accuracy recommended by the instruction for rock and earth's surface shear monitoring in the course of underground mining of ore deposits introduces a significant error in rock mass SSS determination.

As of today, it is established that at intervals with a period of 10 years, geotectonic processes in the Earth's crust result in stress state redistribution [7–9].

The objective connected with the determination of the modern stress field acting in a rock mass in the course of ore deposits mining at different stages remains crucial. The solution will allow more objective elaboration of actions on safe operation of buildings and structures and their protection from underground mining, calculate the earth's surface deformation in the smooth shear zone, and evaluate the stability of underground mine workings.

Formulation of the problem. Currently, mine surveying at mining enterprises is carried out using modern electronic total stations and navigation positioning systems (GLONASS and GPS) [9, 10], which determine the coordinates of surveying reference network points and the state geodetic network (SGN) points in plan to a precision of 1 to 5 mm. The surveying reference network and the state geodetic network are created before the start of the mineral deposit development, and obviously before the caved area outcrop. Therefore, to determine the tectonic field of principal normal stresses acting in a rock mass, it is possible to use the shifts of surveying reference network points and SGN points, caused by rock and the earth's surface shear at the caved area outcrop.

Long-term experience of instrumental observations of surveying reference network points shifts at the caved area outcrop in the course of iron ore deposits development shows that the absolute horizontal deformations of the points varied from 1 to 10 cm [1, 12, 13].

The use of modern electronic total stations and global positioning systems will significantly improve the accuracy of absolute horizontal shifts determination and, consequently, stresses determination.

Methods of research and scope of results. To determine the vectors of horizontal shifts of surveying reference network points and SGN points located on the earth's surface, as well as the horizontal shifts of the upper layers of rocks, with scarcely any pressure on the walls of the outcrop from the caved rock, it is possible to use the solution of the plane elasticity problem. A scheme is proposed for determining the absolute horizontal shifts of surveying reference network points and the SGN points and calculating the tectonic horizontal stresses acting in the rock mass, for a circular hole (Figure 1).

The full vectors of surveying reference network points and the SGN points shifts on the earth's surface are determined from the expression:

$$\varepsilon = \sqrt{\Delta x^2 + \Delta y^2}, \tag{1}$$

where ε – the full vector of reference network point shifts, m; Δx, Δy – the projection of the full vector of reference network point shifts onto the *x* and *y* coordinate axes, m.

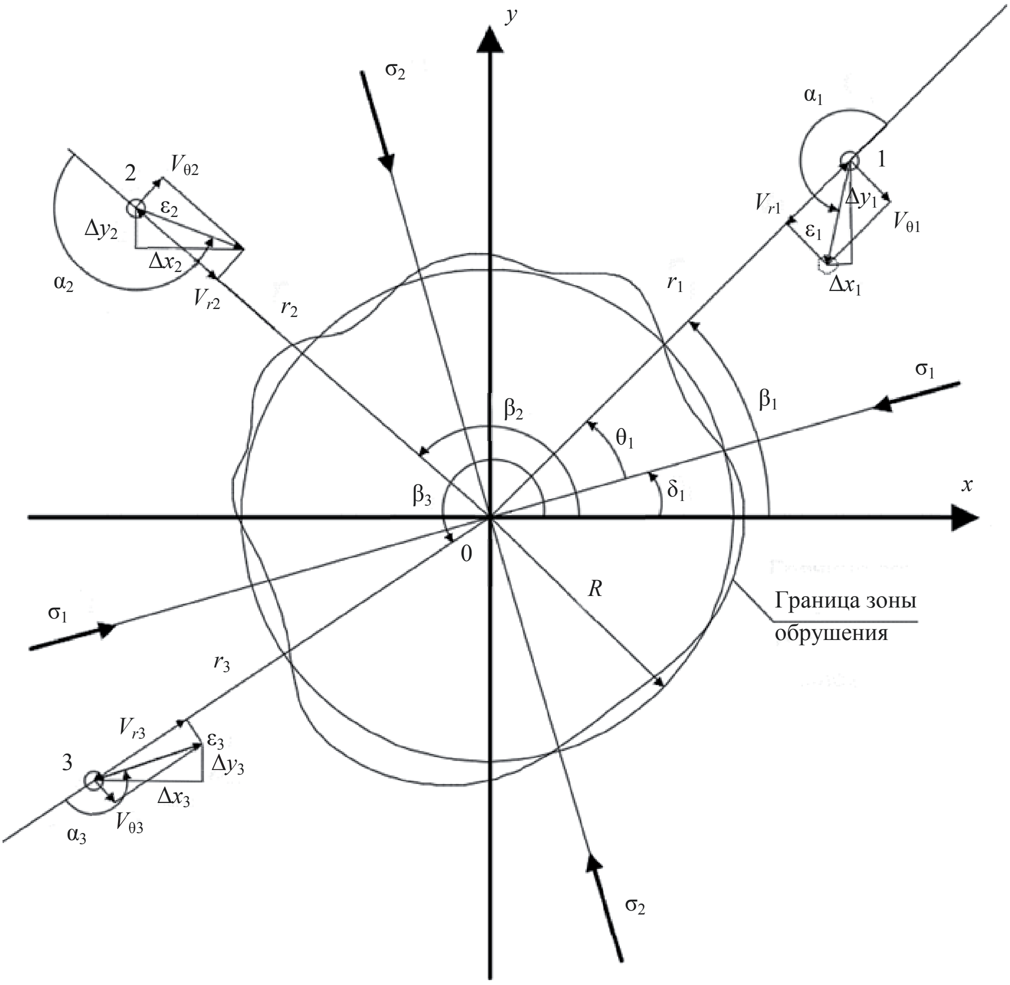

Figure 1. Scheme for the selection of horizontal shifts of the points of the reference surveying network and GGS on the earth's surface and the calculation of horizontal tectonic displacements
Рисунок 1. Схема к определению горизонтальных сдвижений пунктов опорной маркшейдерской сети и ГГС на земной поверхности и расчету горизонтальных тектонических напряжений

Russian [14–18] and foreign literature [19–23] analysis shows that the analytical approach to determining stresses near cavities involves solving and optimizing systems of equations.

The solution of the plane elasticity problem [18] allowed to deduce the horizontal shifts in the following form:

$$\varepsilon = V_r \cos\alpha + V_\theta \sin\alpha; \tag{2}$$

$$\begin{cases} V_r = -\dfrac{\sigma_1-\sigma_2}{4G}\left[\dfrac{R^4}{r^3}-\dfrac{R^2}{r}(x+1)\right]\cos 2\theta + \dfrac{\sigma_1+\sigma_2}{4G}\dfrac{R^2}{r}; \\ V_\theta = \dfrac{\sigma_1-\sigma_2}{4G}\left[\dfrac{R^4}{r^3}+\dfrac{R^2}{r}(x-1)\right]\sin 2\theta, \end{cases} \tag{3}$$

where V_r, V_θ are radial and tangential shifts; α is the angle between the radius vector of the point and the direction of the full vector of the shear; σ_1 and σ_2 are principal normal stresses; R is the hole radius; r is radius vector of the point; $G = E/(2(1-\mu))$ is the shear modulus, E is the deformation modulus; μ is the Poisson's ratio; $x = (3-\mu)/(1+\mu)$ is the coefficient of G. V. Kolosov; θ is the angular coordinate of the point, measured counterclockwise from σ_1 to the radius vector of the point.

Research results. Formulae (1)–(3) make it possible to deduce the following system of equations to determine horizontal tectonic stresses and their direction:

$$\begin{cases} \varepsilon_1 = \left(-\left[\dfrac{R^4}{r_1^3}-\dfrac{R^2}{r_1}(x+1)\right]\dfrac{\sigma_1-\sigma_2}{4G}\cos 2\theta_1 + \dfrac{\sigma_1+\sigma_2}{4G}\dfrac{R^2}{r_1}\right)\cos\alpha_1 + \\ + \left(\left[\dfrac{R^4}{r_1^3}+\dfrac{R^2}{r_1}(x-1)\right]\dfrac{\sigma_1-\sigma_2}{4G}\sin 2\theta_1 + \dfrac{\sigma_1+\sigma_2}{4G}\dfrac{R^2}{r_1}\right)\sin\alpha_1; \\ \varepsilon_2 = \left(-\left[\dfrac{R^4}{r_2^3}-\dfrac{R^2}{r_2}(x+1)\right]\dfrac{\sigma_1-\sigma_2}{4G}\cos 2\theta_2 + \dfrac{\sigma_1+\sigma_2}{4G}\dfrac{R^2}{r_2}\right)\cos\alpha_2 + \\ + \left(\left[\dfrac{R^4}{r_2^3}+\dfrac{R^2}{r_2}(x-1)\right]\dfrac{\sigma_1-\sigma_2}{4G}\sin 2\theta_2 + \dfrac{\sigma_1+\sigma_2}{4G}\dfrac{R^2}{r_2}\right)\sin\alpha_2; \\ \varepsilon_3 = \left(-\left[\dfrac{R^4}{r_3^3}-\dfrac{R^2}{r_3}(x+1)\right]\dfrac{\sigma_1-\sigma_2}{4G}\cos 2\theta_3 + \dfrac{\sigma_1+\sigma_2}{4G}\dfrac{R^2}{r_3}\right)\cos\alpha_3 + \\ + \left(\left[\dfrac{R^4}{r_3^3}+\dfrac{R^2}{r_1}(x-1)\right]\dfrac{\sigma_1-\sigma_2}{4G}\sin 2\theta_3 + \dfrac{\sigma_1+\sigma_2}{4G}\dfrac{R^2}{r_3}\right)\sin\alpha_3. \end{cases} \tag{4}$$

The angular coordinate of the *i*-th point is determined by the following formula:

$$\theta_i = \theta_1 + (\beta_i - \beta_1),$$

where θ_1 is the angle between σ_1 and the radius vector of the first point; β_1, β_i – the angle between the x-axis and the radius vector of the first point and the *i*-th point respectively.

The transformation of the system of equations (4) made it possible to write it as:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + a_{13}x_3 = b_1; \\ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 = b_2; \\ a_{31}x_1 + a_{32}x_2 + a_{33}x_3 = b_3, \end{cases} \tag{5}$$

where a_{11}, …, a_{33} are the coefficients of the equations; b_1, b_2, b_3 are the absolute terms of equations.

The coefficients of the equations are:

$$\begin{cases} a_{11} = K_1^1 = -\left[\dfrac{R^4}{r_1^3} - \dfrac{R^2}{r_1}(x+1)\right]\cos\alpha_1; \\ a_{12} = K_2^1 = \left[\dfrac{R^4}{r_1^3} - \dfrac{R^2}{r_1}(x-1)\right]\sin\alpha_1; \\ a_{13} = K_3^1 = \dfrac{R^2}{r_1}\cos\alpha_1, \end{cases}$$

$$\begin{cases} a_{21} = K_1^2\cos 2(\beta_2 - \beta_1) - K_2^2\sin 2(\beta_2 - \beta_1); \\ a_{22} = K_1^2\sin 2(\beta_2 - \beta_1) + K_2^2\cos 2(\beta_2 - \beta_1); \\ a_{23} = K_3^2 = \left(R^2/r_2\right)\cos\alpha_2, \end{cases}$$

$$\begin{cases} a_{31} = K_1^3\cos 2(\beta_3 - \beta_1) - K_2^3\sin 2(\beta_3 - \beta_1); \\ a_{32} = K_1^3\sin 2(\beta_3 - \beta_1) + K_2^3\cos 2(\beta_3 - \beta_1); \\ a_{33} = K_3^3 = \left(R^2/r_3\right)\cos\alpha_3, \end{cases}$$

$$\begin{cases} K_1^i = -\left[\dfrac{R^4}{r_i^3} - \dfrac{R^2}{r_i}(x+1)\right]\cos\alpha_i; \\ K_2^i = \left[\dfrac{R^4}{r_i^3} + \dfrac{R^2}{r_i}(x-1)\right]\sin\alpha_i; \\ K_3^i = \dfrac{R^2}{r_i}\cos\alpha_i, \end{cases}$$

where K_1^i, K_2^i, K_3^i are the coefficients of the *i*-th point;

$$x_1 = (\sigma_1 - \sigma_2)\cos 2\theta_1; \qquad x_2 = (\sigma_1 - \sigma_2)\sin 2\theta_1; \qquad x_3 = \sigma_1 + \sigma_2;$$
$$b_1 = \varepsilon_1 4G; \qquad b_2 = \varepsilon_2 4G; \qquad b_3 = \varepsilon_3 4G.$$

The solution of the system of equations (5) makes it possible to calculate the value of the principal stresses σ_1 and σ_2 and angle θ using the formulas:

$$\sigma_{1,2} = \frac{1}{2}\left(\frac{\Delta_2}{\Delta} \pm \frac{\Delta_1}{\Delta}\sqrt{1 + \left(\frac{\Delta_2}{\Delta_1}\right)^2}\right);$$

$$2\theta_1 = \operatorname{arctg}\frac{\Delta_2}{\Delta_1},$$

$$\Delta = \begin{vmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{vmatrix}; \qquad \Delta_1 = \begin{vmatrix} b_1 & a_{12} & a_{13} \\ b_2 & a_{22} & a_{23} \\ b_3 & a_{32} & a_{33} \end{vmatrix};$$

$$\Delta_2 = \begin{vmatrix} a_{11} & b_1 & a_{13} \\ a_{21} & b_2 & a_{23} \\ a_{31} & b_3 & a_{33} \end{vmatrix}; \quad \Delta_3 = \begin{vmatrix} a_{11} & a_{12} & b_1 \\ a_{21} & a_{22} & b_2 \\ a_{31} & a_{32} & b_3 \end{vmatrix},$$

where Δ, Δ_1, Δ_2, Δ_3 are the equation determinants.

The value of the angle $2\theta_1$ is not uniquely defined. To determine the quadrant in which it is counted, the signs of ratios Δ_2/Δ and Δ_1/Δ are used.

The direction of the principal normal tectonic stresses acting in the horizontal plane is determined by angle δ_1, which is plotted counterclockwise from the *x*-axis and determined using the following expression:

$$\delta_1 = \beta_1 - \theta_1 .$$

Conclusions. The article describes a method for modern stress field determination when mining ore deposits. The method is based on the shifts of the SGN points and surveying reference network points of the mining enterprises that develop mineral deposits by the underground method with roof strata caving and a circular hole opening up on the earth's surface. To monitor the shifts of the SGN points and surveying reference network points, modern electro-optical total stations and global positioning systems GLONASS and GPS are used. This method makes it possible to determine the values and direction of the principal normal stresses acting in the horizontal plane.

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Определение современного поля напряжений при разработке рудных месторождений

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Реферат

Введение. *В статье дано описание метода определения современного поля напряжений в массиве горных пород при разработке рудных месторождений, когда на земной поверхности образуется провал в виде окружности. Данный метод позволяет определить значения главных нормальных напряжений в верхней части массива горных пород с использованием современных высокоточных электронно-оптических инструментов и систем глобального позиционирования для наблюдений за горизонтальными смещениями пунктов маркшейдерской опорной сети, заложенных на земной поверхности в зоне плавных сдвижений.*

Постановка задачи. *При подземной разработке рудных месторождений подземным способом одним из основных вопросов является обеспечение безопасного состояния подземных горных выработок, зданий и сооружений на земной поверхности. Решение* *данной геомеханической проблемы требует определения современного напряженного состояния массива горных пород. В работе предлагается для определения величины и направления главных нормальных тектонических напряжений, действующих в горизонтальной плоскости, использовать плановые смещения пунктов опорной маркшейдерской сети и пунктов государственной геодезической сети (ГГС), находящихся в зоне плавных сдвижений при образовании на земной поверхности провала, близкого по форме к окружности.*

Цель исследования *– разработать математический аппарат, позволяющий определять современные главные напряжения, действующие в горизонтальной плоскости при выходе зоны обрушения на земную поверхность.*

Основной задачей *исследования является обоснование возможности использования при расчетах напряженного состояния массива горных пород плановых смещений опорных пунктов маркшейдерской сети и пунктов ГГС, измеряемых с помощью современных электронно-оптических приборов и систем глобального позиционирования (ГЛОНАСС и GPS).*

Методы исследования. *Для разработки математического аппарата при определении современных главных тектонических напряжений, действующих в горизонтальной плоскости, используется решение плоской задачи теории упругости.*

Область применения. *Данный метод рекомендуется использовать для определения напряженного состояния массива горных пород на больших базах при разработке рудных месторождений.*

Результаты. *Получены аналитические выражения, позволяющие определять современные тектонические напряжения и направление их действия в горизонтальной плоскости при образовании на земной поверхности провала, имеющего форму окружности. Для определения напряжений используются горизонтальные смещения пунктов опорной маркшейдерской сети и ГГС.*

Ключевые слова: *главные нормальные напряжения; зона плавных сдвижений; зона обрушения; горизонтальные деформации; напряженно-деформированное состояние; массив горных пород; провал; горизонтальные смещения; радиус провала; радиус-вектор.*

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