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Predicting changes in induced seismicity on the basis of estimated rock mass *energy states*

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1. Introduction

Seismic activity occurs during the extraction of a number of minerals in many countries.[1–3] This phenomenon is one of the greatest natural threats in Polish hard-coal mines. Strong mine tremors can produce rock bursts and often cause easily noticeable ground vibrations. Moreover, induced seismicity can lead to the crumbling of coal seams, increasing the risk of endogenous fire or the release of methane, with a consequent risk of explosion.

Observation of seismicity in Polish mines has led to the identification of two types of tremor, described by Gibowicz and Kijko.[4] (a) Very frequent tremors related directly to mining activity. Their foci move with the progress of longwalls and galleries. The number of tremors is strongly correlated to the type of mine work being undertaken and to local geology. (b) Relatively rare high-energy tremors, less sensitive to mining activity. Some of these occur at a considerable distance from the mine. They are more regional than local, and their causes cannot be clearly linked to the extraction of coal from a seam or to the deforming of tremor-prone rock layers by mining activities. They are less frequent, and so have been studied less. Typically, they are related to tectonic faults.

The undisputed connection between tremors related to the low-energy modal value of energy distribution and mine working has inspired many studies intended to describe the links between the parameters for mining activity and the strength of induced seismicity.

Most of the studies of the relationship between seismicity and geological or mining conditions have been empirical. Among the very large number of studies along these lines, Refs. 5–10 may be mentioned. Most of the published work gives the results of qualitative analyses of the effect of specific factors on recorded seismic activity. Since these studies have mostly been qualitative, their results can be used only to a limited extent in the prediction of seismic threats.

Furthermore, deformation processes taking place in the rock mass can contribute to the seismic activity induced by mining. The possibility of taking into consideration specific figures so as to describe the processes deforming tremor-prone rock layers and the land surface as part of induced seismicity studies has been mentioned in a number of published papers, such as the works of Bańka[11] and Białek et al.[12]

Srinivasan et al.[13] showed correlations between induced seismicity and the quantity of mineral extracted, aggregate seismic energy and the frequency of rock bursts, and between the incidence of rock bursts and frequency of tremors in one of the world's deepest gold mines, which descends to a depth of approximately 3.3 km. Similar relationships were discovered by Cai et al.,[14] who also took account of the depth of the mine, the distance from tectonic faults and two factors determined by the regression analysis method, the first describing the effects of extraction, the other being a constant.

Jaworski demonstrated in his works[15,16] correlations between estimated rock mass energy changes and induced seismicity. The description of energy change relates exclusively to the specific energy of elastic strain accumulated in the rock mass as a result of mining activities, without addressing the quantities of energy released by the destruction of a specific volume of rock. As a result of this process, the potential energy of elastic strain is transformed into other non-measurable energy types, including the kinetic energy of elastic strain waves (seismic energy of recorded tremor), as stated by Salamon.[17] It is

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in this way that changes in potential energy affect the induced seismicity observed.

This article discusses the use of computed specific energy changes in predicting tremor energy output. It provides an example of the prediction of induced seismicity in a hard-coal mine.

2. Proposed method using the relationship between estimated specific energy change and the level of induced seismicity

The energy of elastic strain is the energy stored by a system undergoing deformation. The specific energy of elastic strain is the result of the work of deformation expressed as the product of forces (stresses σ, τ) and corresponding dislocations (strains ε, γ). The following known Clapeyron equation describes the specific energy of elastic strain:

$$\Phi = 0.5\ T_\sigma T_\varepsilon, \tag{1}$$

where Φ is the specific energy of elastic strain (in joules per cubic metre [J/m^3]), and T_σ and T_ε the stress (in MPa) and strain tensors, respectively.

In order to determine the value of specific energy of elastic strain at a particular point, or its changes during mining, it is necessary to know the changing time components of the state of stress and strain tensors. To achieve this, we apply an analytical method based on the solution proposed by Gil[18] for the dislocation boundary value problem of the spatial theory of elasticity, defining the distribution of stresses and strains within a half-space around a rectangular void.

According to the just mentioned solution, which is reduced to determining a single harmonic function f_3 (see 18), with the following boundary conditions:

$$\tau_{xz} = \tau_{yz} = 0 \text{ for the whole plane } z = 0, \tag{2}$$

$$u_z(x, y, 0) = \begin{cases} -w_0 \text{ for } |x| \le d_1,\ |y| \le d_2 \\ 0 \text{ over the remaining area} \end{cases}, \tag{3}$$

and taking into account that as $z \to \infty$ all components of the stress decrease to 0, the displacements u_x, u_y, u_z produced in the basic rectangular extraction having the dimensions $2d_1 \times 2d_2$ yield the following relations:

$$u_x = f_1 - \frac{z}{2(1-\nu)}\frac{\partial f_3}{\partial x} \tag{4}$$

$$u_y = f_2 - \frac{z}{2(1-\nu)}\frac{\partial f_3}{\partial y} \tag{5}$$

$$u_z = f_3 - \frac{z}{2(1-\nu)}\frac{\partial f_3}{\partial z} \tag{6}$$

where functions f_1, f_2, f_3 satisfy the Laplace equations, and have the form:

$$f_1 = \frac{1-2\nu}{2(1-\nu)}\int_z^\infty \frac{\partial f_3}{\partial x}dz \quad f_2 = \frac{1-2\nu}{2(1-\nu)}\int_z^\infty \frac{\partial f_3}{\partial y}dz \tag{7}$$

$$f_3 = -\frac{w_0}{2\pi}\left\{ arctg\frac{(d_1-x)(d_2+y)}{zr_1} + arctg\frac{(d_1+x)(d_2-y)}{zr_2} + arctg\frac{(d_1+x)(d_2+y)}{zr_3} + arctg\frac{(d_1-x)(d_2-y)}{zr_4} \right\} \tag{8}$$

where

$$r_1^2 = (d_1-x)^2 + (d_2-y)^2 + z^2, \quad r_2^2 = (d_1+x)^2 + (d_2-y)^2 + z^2 \tag{9}$$

$$r_3^2 = (d_1+x)^2 + (d_2+y)^2 + z^2, \quad r_4^2 = (d_1-x)^2 + (d_2+y)^2 + z^2 \tag{10}$$

Knowing the components of the displacement vector, the components of the strain and the stress tensors can be found from the generalized Hooke equation:

$$\sigma_x = \frac{G}{(1-\nu)}\left[2\nu\frac{\partial f_3}{\partial z} + 2(1-\nu)\frac{\partial f_1}{\partial x} - z\frac{\partial^2 f_3}{\partial x^2}\right],\ \varepsilon_x = \frac{\partial f_1}{\partial x} - \frac{z}{2(1-\nu)}\frac{\partial^2 f_3}{\partial x^2}, \tag{11}$$

$$\sigma_y = \frac{G}{(1-\nu)}\left[2\nu\frac{\partial f_3}{\partial z} + 2(1-\nu)\frac{\partial f_2}{\partial y} - z\frac{\partial^2 f_3}{\partial y^2}\right],\ \varepsilon_y = \frac{\partial f_2}{\partial y} - \frac{z}{2(1-\nu)}\frac{\partial^2 f_3}{\partial y^2}, \tag{12}$$

$$\sigma_z = \frac{G}{(1-\nu)}\left[\frac{\partial f_3}{\partial z} - z\frac{\partial^2 f_3}{\partial z^2}\right],\ \varepsilon_z = \frac{\partial f_3}{\partial z} - \frac{z}{2(1-\nu)}\frac{\partial^2 f_3}{\partial z^2}, \tag{13}$$

$$\tau_{zx} = \frac{-G}{1-\nu}z\frac{\partial^2 f_3}{\partial x \partial z},\ \gamma_{zx} = \frac{-z}{1-\nu}\frac{\partial^2 f_3}{\partial x \partial z}, \tag{14}$$

$$\tau_{zy} = \frac{-G}{1-\nu}z\frac{\partial^2 f_3}{\partial y \partial z},\ \gamma_{zy} = \frac{-z}{1-\nu}\frac{\partial^2 f_3}{\partial y \partial z} \tag{15}$$

$$\tau_{xy} = \frac{G}{1-\nu}\left[(1-\nu)\left(\frac{\partial f_1}{\partial y} + \frac{\partial f_2}{\partial x}\right) - z\frac{\partial^2 f_3}{\partial x \partial y}\right],\ \gamma_{xy} = \frac{\partial f_1}{\partial y} + \frac{\partial f_2}{\partial x} - \frac{z}{1-\nu}\frac{\partial^2 f_3}{\partial x \partial y} \tag{16}$$

where w_0 is the displacement of the seam roof above the worked area (in m), G is the modulus of rigidity (in mega pascals [MPa]).

According to Jaworski[15] the algorithm for calculating component values of the tensor of stresses and strains consists of the illustrated steps in Fig. 1, and explained in what follows. Digitalization of the rectangular area for calculations is carried out and a network of calculation points is set. The entire calculation cycle is repeated for all of the points in the network. Next, components p_x, p_y and p_z of the primary stress are calculated. Primary stresses produced by the weight of overlying rocks are computed using the following known relations:

$$p_z = -\gamma \mathrm{H}(\cos^2\alpha + n\sin^2\alpha)$$

$$p_x = p_y = -\gamma \mathrm{H}(\sin^2\alpha + n\cos^2\alpha); \quad n = \frac{\nu}{1-\nu} \tag{17}$$

where H is the depth of the deposit (in metres [m]), γ is the average weight per volume of overlying rocks (in kilograms per cubic metre [kg/m^3]), n is the horizontal expansion ratio, ν is the Poisson ratio, and α is the stratum tilt angle (in degrees). On the basis of the value Δt introduced for time steps and the time-based range of mining analysed, the number l_{dt} of time intervals Δt is defined. The program generates tables $\sigma_x(1,\ldots,l_{dt})$, $\sigma_y(1,\ldots,l_{dt}),\ldots,\tau_{zy}(1,\ldots,l_{dt})$ and $\varepsilon_x(1,\ldots,l_{dt})$, $\varepsilon_y(1,\ldots,l_{dt}),\ldots,\gamma_{zy}(1,\ldots,l_{dt})$, where the increasing values over time of successive components of tensors of stress and strain states are recorded.

For each extraction plot the following procedures are undertaken: the whole plot is divided into elementary strips parallel to the longwall cross-section. The width of the strips corresponds to the advancement of the longwall in the time interval Δt. The strips are trapezoidal in shape. When the stripes are sufficiently narrow, the trapezoids corresponding to them may be converted into equivalent rectangles, to which the equations of H. Gil can be applied. Making use of the equations above, together with those relating to the transformation of the components of stress and strain tensors, allows the increase in stresses and strains caused by mining successive parts of the plot to be calculated (successive stripes). The components of these increases are added to the values for increasing stresses and strains arising from the mining of other longwalls during the same time interval. The sequences of figures for increasing stresses and strains from tables: $\sigma_x(1,\ldots,l_{dt})$, $\sigma_y(1,\ldots,l_{dt}),\ldots,\tau_{zy}(1,\ldots,l_{dt})$ and $\varepsilon_x(1,\ldots,l_{dt})$, $\varepsilon_y(1,\ldots,l_{dt}),\ldots,\gamma_{zy}(1,\ldots,l_{dt})$, are transformed into sequences of components, varying over time, of tensors of stresses and strains. The respective values for the components of primary stress p_x, p_y and p_z are added to components σ_x, σ_y and σ_z.

The rock mass model (as a continuous, homogeneous, isotropic and linearly elastic medium) represents a major simplification over any