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Method of forecasting seismic energy induced by longwall exploitation based on changes in ground subsidence

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ABSTRACT

A method of forecasting total seismic energy induced by longwall exploitation, based on changes in ground subsidence, is presented in the form of a linear regression model with one with one independent variable. In the method, ground subsidence is described with a cross-section area of a subsidence trough *Pw* along a line of observations in the direction of an advancing longwall front, approximately along the axis of the longwall area. Total seismic energy is determined on the basis of seismic energy data of tremors induced by exploitation. The presentation consists of a detailed method and evaluation of its predictive ability for the area of longwall exploitation within the region of one of the coal mines in the Upper Silesian Coal Basin. This method can be used for forecasting the total seismic energy released by tremors within the area directly connected with the exploitation, in which the seismic activity induced by this exploitation occurs. The estimation of the parameters of the determined model should each time be carried out with investigations of the correctness of the model. The method cannot be applied when the number of recorded phenomena is small and when there is insufficient data to make it possible to calculate the index *Pw*.

1. Introduction

Mining exploitation of hard coal in Poland has been carried out for many years and in most cases, within areas of induced seismic activity. There is a constant increase of natural hazards in active mines. Approximately 45% of the present output comes from strata considered to be of high risk rock burst hazard. The potential level of seismic hazard has increased. Changes in the status of rock burst and tremor hazards are significantly affected by mining technology and the state of knowledge enabling forecasting and introducing suitable preventive actions. This is why the problem of induced seismic activity is a subject of many investigations. As a result, new measurement methods, extensive elaboration, interpretation and seismic hazard forecasting methods have been developed in recent years. Forecasting is always one of the most important tasks during exploitation under induced seismic activity. Given these conditions, measures are in place to minimize the risk of these adverse effects. In general, hazards in areas under study and research are established on the basis of past data, which enables us to determine seismic activity indices, updated as new data are acquired. The forecast can include surroundings of a single excavation or areas directly connected with exploitation. Tremor generation processes are considered a function of time.

The indices of seismic activity of a rock mass, induced by exploitation, can be the number of tremors registered or energy released in a given period of time. Seismic activity levels can be characterized as index defining deformation processes of rock mass layers, which can generate tremors and indices of surface deformation [1–6].

This study presents a method of forecasting total seismic energy induced by longwall exploitation, based on changes in ground subsidence, using a linear regression model with one independent variable. The method presented has been elaborated on the basis of results of research carried out since 2004 in the Institute of Mining of the Silesian University of Technology [7–12]. The ground subsidence is described for by a cross-section area of a subsidence trough *Pw* along an observational line, in the direction of the advancing longwall front, approximately in the middle of the face of the longwall. The forecast is executed on the basis of a defined linear regression model of total increasing seismic energy with respect to increases in the *Pw* area. After verifying the model and in case it is considered sufficiently accurate, the forecast of a total seismic energy is executed within a time period *T*, during which the cross-section area reaches its predicted value. The level of accuracy of executed forecasts is defined on the basis of the relative error of the ex ante forecast. This forecast accuracy is evaluated based on the average absolute percentage error of ex post forecasts.

The study consists of a detailed algorithm and evaluation of its predictive abilities for the area of longwall exploitation, executed

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within the region of one of the coal mines in the Upper Silesian Coal Basin.

2. Model of seismic energy regression induced by exploitation with respect to ground subsidence

A linear regression model with one independent variable was used for a description of the interdependence between induced seismic energy and observed ground subsidence. The model defines the relationship between total increasing seismic energy of tremors E emitted by the end of a time period, defined by the execution date of i–nth geodetic measurement cycle (E_i) and the cross-section area of the subsidence trough Pw along an observational line in the direction of the advancing longwall front, approximately in the middle of the face of the longwall, in the i–nth cycle (Pw_i). The area was taken as the index describing the ground subsidence (Fig. 1). It is determined on the basis of periodic geodetic measurements made for the observed region of longwall exploitation. Total seismic energy is determined on the basis of data from the seismic energy of registered tremors induced by this exploitation.

The index Pw was established after Kijko, who assumed correlation between the volume of the formed cavern in the rock mass and its observed seismic activity [13]. It was therefore obvious that the relationship between the volume of the subsiding trough formed on the ground and the seismic emission of the rock mass, as the volume of trough, is dependent on the volume of the formed cavern. At the same time, it was also assumed that the volume of the observed trough corresponded better to the true movements of the rock mass than did the volume of the trough formed as a result of the exploitation of the cavern in the rock mass.

Working hypothesis: interdependence between the volume of the subsidence trough formed on the surface and observed seismicity of the rock mass is assumed.

Geodesic measurements using especially designed observation lines are performed on the surface during mine exploitation. One of the lines is usually situated along an advancing longwall front. Thus, most of our observations of changes in the size of the points are in the line of observations along the longwall area, which by necessity leads to the adoption of the simplified assumption that the volume of the formed trough changes in time proportionally to the cross-section area Pw of the subsiding trough, formed along the observation line.

The regression model is stated as (1):

$$E_i = \alpha + \beta Pw_i + \varepsilon_i \quad (i = 1, 2, \ldots, n) \tag{1}$$

where E_i is the total increasing seismic energy emitted at the end of a time period, defined by the execution date of the i–nth geodetic measurement cycle, J; Pw_i the cross-section area of subsidence trough in the i–nth geodetic measurement cycle, m^2; α the absolute term, β the regression coefficient, ε_i the random variable defined as

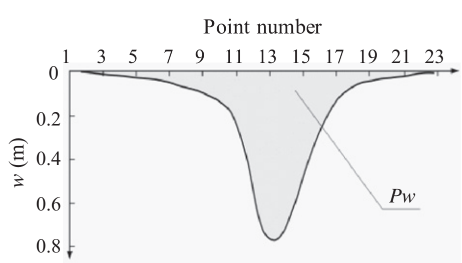

Fig. 1. Measured ground area points of subsidence w along the line of observations within the geodetic measurements cycle, Pw-cross-section area of subsidence trough evaluated in a given cycle.

a random component clarifying the dispersion of E_i values $\varepsilon_i \approx N(0, \sigma^2)$, and n the number of observations (number of geodetic measurement cycles $i = 1, 2, \ldots, n$). The regression equation was solved with the following assumptions:

The variance of the random variable ε_i is the constant value σ^2: i.e., $D^2(\varepsilon_i) = \sigma^2$.

The random components are not correlated, i.e., $\mathrm{cov}(\varepsilon_i, \varepsilon_j) = 0$, for $i \neq j$, where $i, j = 1, 2, \ldots, n$.

Estimation of the parameters was carried out using the method of least squares. The estimators of the parameters α and β were designated as a and b (2) and (3):

$$b = \frac{\sum_{i=1}^{n} Pw_i E_i - [(\sum_{i=1}^{n} Pw_i)(\sum_{i=1}^{n} E_{ii})]/n}{\sum_{i=1}^{n} Pw_i^2 - (\sum_{i=1}^{n} Pw_i)^2/n} \quad (i = 1, 2, \ldots, n) \tag{2}$$

$$a = \overline{E} - b\overline{Pw} \tag{3}$$

where

$$\overline{E} = \left(\sum_{i=1}^{n} E_i\right)\Big/n, \quad \overline{Pw} = \left(\sum_{i=1}^{n} Pw_i\right)\Big/n$$

In which n is the number of observations (number of geodetic measurement cycles), and other definitions as above.

Given these definitions, the regression function can be written as (4):

$$\widehat{E}_i = a + bPw_i \quad (i = 1, 2, \ldots, n) \tag{4}$$

Values of this $\widehat{E}_i$ function, calculated for Pw_i, are referred to as expected values. Differences were defined as the residuals e_i (5):

$$e_i = E_i - \widehat{E}_i \quad (i = 1, 2, \ldots, n) \tag{5}$$

where E_i is the observed values, $\widehat{E}_i$ the expected value, n the number of observations (number of geodetic measurement cycles).

The standard deviation estimator σ of the random components is the standard deviation of the residuals S_e, defined as (6):

$$S_e = \sqrt{\frac{\sum_{i=1}^{n} e_i^2}{n-2}} \tag{6}$$

Standard errors of the estimated parameters α, β are defined as S_a, S_b and determined from the following Eqs. (7) and (8):

$$S_a = S_e \sqrt{\frac{\sum_{i=1}^{n} Pw_i^2}{n \sum_{i=1}^{n} (Pw_i - \overline{Pw})^2}} \tag{7}$$

$$S_b = \frac{S_e}{\sqrt{\sum_{i=1}^{n} (Pw_i - \overline{Pw})^2}} \tag{8}$$

2.1. Model verification

Model verification was executed based on an examination of the quality of the estimated structural parameters, the degree of conformity of the model with empirical data and the distribution of the standard deviation.

Validity of the parameter β was determined on the basis of a t statistic (9):

$$t = \frac{b - \beta}{S_b} \tag{9}$$

which, assuming a normal distribution, has a Student t distribution with $(n-2)$ degrees of freedom. After considering the null hypothesis H_0: [$\beta = 0$], the statistic is defined as in (10):

$$t = \frac{b}{S_b} \tag{10}$$