Forecasting of Energy Expenditure of Induced Seismicity with Use of Artificial Neural Network

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Abstract. Coal mining in many Polish mines in the Upper Silesian Coal Basin is accompanied by high levels of induced seismicity. In mining plants, the methods of shock monitoring are improved, allowing for more accurate localization of the occurring phenomena and determining their seismic energy. Equally important is the development of ways of forecasting seismic hazards that may occur while implementing mine design projects. These methods, depending on the length of time for which the forecasts are made, can be divided into: long-term, medium-term, short-term and so-called alarm. Long-term forecasts are particularly useful for the design of seam exploitations. The paper presents a method of predicting changes in energy expenditure of shock using a properly trained artificial neural network. This method allows to make long-term forecasts at the stage of the mine's exploitation design, thus enabling the mining work plans to be reviewed to minimize the potential for tremors. The information given at the input of the neural network is indicative of the specific energy changes of the elastic deformation occurring in the selected, thick, resistant rock layers (tremor-prone layers). Energy changes, taking place in one or more tremor-prone layers are considered. These indicators describe only the specific energy changes of the elastic deformation accumulating in the rock as a consequence of the mining operation, but does not determine the amount of energy released during the destruction of a given volume of rock. In this process, the potential energy of elastic strain transforms into other, non-measurable energy types, including the seismic energy of recorded tremors. In this way, potential energy changes affect the observed induced seismicity. The parameters used are characterized by increases (declines) of specific energy with separation to occur before the hypothetical destruction of the rock and after it. Additional input information is an index characterizing the rate of tectonic faults. This parameter was not included in previous research by authors. At the output of the artificial neural network, the values of the energy density of the mining tremors [J/m³] are obtained. An example of the predicted change in seismicity induced for a highly threatened region is presented. Relatively good predicted and observed energy expenditure of tremors was obtained. The presented method can complement existing methods (analytical and geophysical) forecasting seismic hazard. This method can be used primarily in those areas where the seismic level is determined by the configuration of the edges and residues in the operating seam, as well as in adjacent seams, and to a lesser extent, the geological structure of the rock. The method is local, it means that the artificial neural network prediction can only be performed for the region from which the data have been used for its originated learning. The developed method cannot be used in areas where mining is just beginning and it is not possible to predict the level of seismicity induced in areas where no mining tremors have been recorded so far.
1. Introduction
The exploitation of hard coal in Poland and in the world is very dangerous. There are many natural hazards in it, the most dangerous of them are seismic [1, 2, 3] and ventilation hazards [4]. The seismic threat is occurring in an increasing number of areas in Poland exploiting hard coal. Despite the declining output of this raw material, there is no proportional reduction in the number of strong tremors and their maximum energy. There are a number of reasons for this: the increasing depth of exploitation, the need to carry out works in residual batches in the vicinity of large discharges of tectonic dislocations, and the increasing concentration of extraction due to the limitation of the supply of works and the need of increasing the efficiency of mining production. The high level of seismic risk will most likely accompany many of the mining projects currently under development, so it is important to improve the methods of forecasting this threat.

The paper presents the developed method of forecasting changes in the magnitude of induced seismicity using artificial neural networks (ANN). The information given on the grid entry are an indicators of the course of energy changes in the rock and its degree of bed drop. The quantitative description of energetic changes refers only to the energy of the elastic strain accumulating in the rock as a consequence of the mining operation, but does not determine the amount of energy released in the process of destroying given volume of rock. In the process of destruction of the rock layer, the potential energy of elastic strain is converted into other quantifiable quantum energy types, including the kinetic energy of the elastic waves (seismic energy of the recorded tremors) [2]. In this way, potential energy changes affect the observed induced seismicity. The study also includes the effect of tectonic faults on the observed level of induced seismicity. Of the various rock disturbances indicators considered, the most informative indicator was the ratio representing the ratio of the total tectonic faults length to the considered surface. Below there are the results of the seismic hazard forecast developed for a selected seismic hazard area.

2. Description of the method used to forecast changes in seismic hazards
An analytical method was used to estimate the energetic changes occurring in rocky layers, based on the solution of the displacement boundary problem of the linear elasticity theory given by H. Gil [5], which describes the distribution of stresses and strains in the half-space around the rectangular excavation. The specific energy of elastic strain is determined by the Clapeyron formula:

$$\Phi = 0.5 T_{\sigma} T_{\varepsilon}$$

where: $\Phi$ is specific energy of elastic strain ($J/m^2$), $T_{\sigma}$ is tensor of stress state (MPa), $T_{\varepsilon}$ is tensor of strain state.

Because of the very simple model of the rock, the distribution of stresses and strain must be determined in a comparative manner. This means that the values of the strength parameters are selected so that the results of the test calculations (for the already implemented mining exploitation range) correspond to the results of observation of seismic and rock burst conditions. Quantitative comparisons have shown that in many geo-mining situations, the use of analytical methods allows comparable results to the results obtained using the finite difference method. The great advantage of analytical methods is the high numerical efficiency that is important when it is required to estimate changes in energy states at short intervals. Frequently, fault regions are areas of stress concentration in which the accumulated energy can be triggered as seismic events, creating a real risk of bumps. Very large dislocations of a regional character are well documented. Conducting mining works in their vicinity most often generates high seismicity of the rock, posing a threat to these excavations. The level of seam disturbance is essential for the design of the operation. Its measure is the $G_p$ [m/10^4$m^2$] drop index, which expresses the ratio of the total length ($L$) of the faces recorded on a given surface to the value of that surface. For $G_p$ not exceeding 50 m/10^4$m^2$, the mechanization of exploitation can be used without restrictions, whereas for larger $G_p$ values, the complex mechanization of exploitation works is reduced even further as the index is approaching 250 m/10^4$m^2$.
The surface density index of the faults is calculated according to the following formula:

\[ G_p = \frac{L_u}{F} \]  

(2)

where: \( L_u \) is total length of all faults within the allocated unit area (m), \( F \) is unit area (10 000 m²).

In the conducted research input information introduced into the neural network were an indicators describing changes in specific energy occurring in selected, resistant rock layers (so-called tremor-prone layers). These indices were characterized by increments (decrements) of the specific energy elastic deformation with separation to occur before hypothetical destruction of the rock (effort rate \(<1\)) and after it (effort rate \(\geq1\)). There were considered energy changes taking place in one or more shocking layers. An analogue set of indicators was included in the regression regressions used in previous work to search for induced seismic relationships with calculated indices characterizing the processes of deformation and energy in the rock [1, 6].

These indicators describe the following relationships:
- calculated at the point \( l \) for the \( k \)th rock layer, the sum of instantaneous specific energy increments, when the stress index \( W <1\):
  \[ f_{ikl} = \sum_{i=1}^{kth} \Delta \Phi_{iobl}^{+}(W<1) \]  

(3)
- calculated at the point \( l \) for the \( k \)th rock layer, the sum of instantaneous specific energy decrements, when the stress index \( W <1\):
  \[ f_{2kl} = \sum_{i=1}^{kth} \Delta \Phi_{iobl}^{-}(W<1) \]  

(4)
- calculated at point \( l \) for the \( k \)th rock layer of the sum of instantaneous specific energy decrements, when the stress index \( W \geq1\):
  \[ f_{3kl} = \sum_{i=1}^{kth} \Delta \Phi_{iobl}^{+}(W \geq1) \]  

(5)
- calculated at the point \( l \) for the \( k \)th rock layer, the sum of instantaneous specific energy decrements, when the stress index \( W \geq1\):
  \[ f_{4kl} = \sum_{i=1}^{kth} \Delta \Phi_{iobl}^{-}(W \geq1) \]  

(6)

In addition, the input for the neural network was reported for \( G_p \). The surface density index of the faults calculated from relation 2

In order to select the best neural network characteristics in terms of the number of neurons in the hidden layer and the optimal network architecture, many analyzes are required [6, 7]. For the data set in question, optimal neural network is composed of seventeen neurons in the input layer, two neurons with bipolar characteristics in the hidden layer and one neuron with linear or bipolar characteristics in the output layer.

3. Description of the research area

The article presents an example of a seismic hazard forecast for an area of operation in a highly seismically threatened the Upper Silesian Coal Basin mine. This operation was carried out in the fields of two longwalls 002 and 003 in the seam 504 (Figure 1), whose thickness varies from 2.8 to 7.0 m (the height of the operating bay was 3.4 m). Depth of retention is about 850 m, falling layers \( 4^{\circ} \div 16^{\circ} \) in the southerly direction. In the area of the above-mentioned longwall excavations, overlapping seams
have been exploited, including: 413 at a distance of about 270 m, 416 at a distance of about 160 m, 418 at a distance of about 130 m and 502 at a distance of about 70 m from the seam 504. In the geological profile there are several potentially tremor-prone layers of sandstone. The selected four of them were calculated for specific energy changes occurred during the course of the longwalls 002 and 003. They are layers with thicknesses of about 30 m, 31 m, 23 m and 20 m, respectively at 450 m, 350 m, 100 m. The seam operation 504 was considered to have induced 26 high-energy tremors: 20 with an energy of $10^5$ J and 6 with an energy of $10^6$ J. In addition, 194 phenomena with an energy of $10^4$ J were recorded. In total there were 5,000 tremors with a total energy of about $4 \times 10^7$ J. The strongest tremor occurred while guiding longwall 002 and reached $6 \times 10^6$ J energy. Like the others, it did not cause any effects in mining excavations.

Figure 1. Contours of longwalls 002 and 003 in seam 504 with engraved edges of operation in seams 418 and 502 and tremors foci

4. Results of the research

For the analysed area of exploitation in addition to the previously mentioned studies [7] the indicators characterizing the energy changes, an additional parameter characterizing the degree of tectonic disturbance of the rockmass was added to the analysis. In the first stage of work, qualitative relationships between induced seismicity (location of epicentre shocks) and the course of faults were analyzed. Data on the occurrence of tectonic faults were read from the of the seams. The results of the qualitative analysis are shown in Figure 2.

Figure 2. Faults, shocks - area of longwalls 002 and 003 in seams 504
The results of the qualitative analysis show that there is a qualitative association of the location of the zones in which the increased number of tremors with the location of the faults occurs. Using data on observed seismicity and calculated indices characterizing the change of specific energy and degree of tectonic disturbance of the seam 504 in the field of the first longwall 002, the study of the neural network was conducted. The results of this process are presented in Figures 3 and 4, where Figure 3 shows the value of energy density observed, while Figure 4 shows the value of energy density reconstructed by the trained artificial network.

![Figure 3. Distribution of the shock energy density values [J/m³] observed during the 002 driving time in seams 504](image)

As it can be seen from the comparison of Figures 3 and 4, the artificial neural network allowed a relatively accurate reconstruction of the observed energy expenditure of the tremors. The value of the linear correlation coefficient is 0.9 and the mean square error is 1.3 J/m³.

An appropriately trained neural network was used to predict the energy output of tremors at the run of longwall 003. The results of this prediction are presented in Figure 6. For comparison, Figure 5 shows the tremors energy density observed in longwall 003.
Figure 5. Distribution of the energy density values of shocks [J/m³] observed during the run of longwall 003 in seams 504

Considering, in addition to the energy change indices, a parameter describing the degree rock disturbances, has allowed for relatively accurate prediction results - the average square error is 2.43 J/m³, while the correlation coefficient is 0.64.

Figure 6. Distribution of shear energy density values predicted by neural network in the run of longwall 003 in seams 504

5. Summary
The paper presents the results of research aimed at determining the possibility of using artificial neural networks to predict the level of seismicity induced by mining. The study includes a new, unused during previous investigations parameter that has characterized the rate of collapse of the bed. Data used in the conducted research came from the area of high seismically threatened hard coal mine located in the Upper Silesian Coal Basin (the Upper Silesian Coal Basic mines). The results of the study showed that in the case of the analysed area, the use of the tectonic faults disturbance index gave good results of the shock energy density forecast.

For the recovery of the energy output of the shock that occurred during the guiding of the longwall 002, the value of the linear correlation coefficient is 0.9 and the average square error is 1.3 J/m³. In turn, for the lead-in period of 003 ("true prediction"), the linear correlation coefficient is 0.64 and the mean square error is 2.43 J/m³. Presented results of preliminary studies show that the developed
Energy expenditure of mine tremors method can be also used in areas where the induced seismicity is determined not only by the exploitation and operation parameters, but also by the tectonic disturbances of the rockmass.

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