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Rock bursts prediction based on analyzing maximal phenomena of seismic emission in the INGEO system

Predicting the time of rock bursts in the INGEO system is based on the analysis of seismic emission registered in a seismic-acoustic system. Emission signals are generated by rock mass fracturing due to mining exploitation. Such emission is characterized by huge activity of different phenomena which enables to carry out a correct statistical analysis with the use of the hazard method, achieving suitably high resolution of interpretation results. The hazard method is based on the analysis of maximal phenomena, i.e. phenomena of maximal energy. The use of this method allows to eliminate disturbances to a large extent and, at the same time, enables to assess the probability of high-energy phenomena (rock bursts). The hazard analysis is conducted on the basis of two essential qualities of seismic emission, such as energy of phenomena and intervals between successive phenomena. These qualities are random variables of statistical distribution described by the Weibull model. Using this model one can estimate the parameters of statistical distribution of those qualities which are the basis to determine hazard parameters. The analysis is conducted based on measurement data collected from the T window, i.e. time interval measured by hours. The window is moved with the d step and the calculations are repeated. The hazard parameters were used to define the risk function $FW_t(Q_E,T)$ *which is the measure of rock bursts hazard. This function depends on real time t which is determined as the time of the T window right edge. It is also the basis to work out rock burst hazard criteria. It is important to note that the moment a rock burst occurs is a random variable and can be determined with the accuracy of its confidence interval, with certain probability.*

Key words: *seismic emission, hazard method, stream of events, Weibull model, rock bursts, seismic hazard*

1. INTRODUCTION

Due to underground mining exploitation, unfavourable stress conditions are evoked in the rock mass surrounding the excavations. Once the critical strength values are exceeded, the rocks begin to fracture. The fracturing progresses in a certain manner until a rock burst occurs [9]. Fracturing is a physical phenomenon which is not liable to direct observations. However, it is possible to reason about its progress indirectly, as it generates vibrations which get dispersed in the rock mass in the form of seismic emission [8].

The article is devoted to the issue of working out a method to assess the state of rock burst hazard and predicting the time of rock bursts which was applied in the INGEO system. The analysis is carried out based on two essential qualities of emission, i.e. energy of the phenomena and intervals between successive phenomena. The registered emission is characterized by huge activity, up to several dozen phenomena per minute, by a high degree of randomness and a significantly high level of disturbances. Therefore the investigation of the emission is conducted with the use of probabilistic methods. The concept how to solve the issue, presented in the article, is developed by the analysis of seismic emission maximal phenomena with the use of the hazard method [6]. Thanks to the detection of maximal phenomena, we can significantly eliminate disturbances whose further removal is done during the estimation of statistical distribution of emission characteristics. The use of the stochastic hazard analysis, in turn, enables to assess the probability of maximal energy phenomena (rock bursts). Maximal phenomena are determined on the basis of their energy. It is not possible to locate exactly the sources of emission with respect to low-energy phenomena, i.e. small fractures, as relatively small signals confirming this emission reach a small number of sensors. Therefore it is not possible to assess the physical energy of these phenomena because to determine this energy one has to know the distance between the vibrations source and the registration spot. Thus it was assumed that this energy would be determined as the square of the registered signals standard value [2]. As emission sources are distributed randomly in the rock mass, the energy determined in this manner is subject to statistical dispersion caused by the occurring random factor. The described time intervals are physical quantities and, practically, they do not depend on the spatial distribution of sources and their values can be determined with high accuracy. It is important to note that there is linear statistical dependence between the phenomena energy logarithms and the intervals between the moments of their occurrences. The dependence says that in order to generate high-energy seismic phenomena we need longer intervals. The dependence was formulated and documented in the range of rock bursts for which it was possible to determine physical energy [3]. Therefore it was assumed that in the statistical sense this feature can represent the energy of phenomena indirectly. The listed qualities of seismic emission are random variables with statistical dispersion described by the Weibull model. Being familiar with the statistical dispersion of the discussed features one can assess hazard parameters, provided that the energy of the phenomena exceeds the set level Q_E. The estimation of these quantities is carried out based on data collected from the interval T (window), expressed in hours. Based on the discussed hazard parameters we defined the so called rock burst occurrence risk, assigned to the window T. Then, moving the window with the step d, we will achieve its progress in the form of the risk function $FW_t(Q_E,T)$, whose independent variable is real time t. Based on the progress of this function, it is possible to assess the rock burst hazard degree and to predict the moments of bursts.

2. ASSESSMENT OF ROCK BURST HAZARD AND PREDICTION OF ROCK BURST OCCURRENCE WITH THE USE OF THE HAZARD METHOD

Mining rock bursts are characterized by a significant share of the random factor. Therefore the assessment of rock burst hazards and prediction of bursts occurrence are conducted by stochastic methods. Due to the unfavourable state of stresses, caused by exploitation, the rock mass fractures. Usually, particular fractures are related to one another creating the so called fracturing processes. With high values of stresses, the sizes of fractures grow too. If the burst causes adequate drop of stress values, this is the end of the fracturing process. The presented method is based on the analysis of seismic emission which maps the rock mass fracturing processes. It is assumed that both particular fractures and the resulting emission phenomena have the same random character. The research is conducted on the basis of the emission characteristics, i.e. energy of the phenomena (signals) and intervals between the phenomena which are random variables of the recognized statistical dispersion. Solving these issues by means of probabilistic methods is not conducted directly on the basis of emission characteristics. Contrarily, it is based on the analysis of parameters which describe their statistical dispersion. These parameters are estimated (assessed) based on suitable sets of measurement data. Within the discussed issues, the elements of these sets are seismic phenomena or seismic vibrations signals registered in time intervals (windows) T with a determined size, e.g. one hour. In order to conduct statistical analyses and to achieve the assessment of rock burst hazards, it is necessary to know the law describing statistical dispersions of emission qualities and to be familiar with the model of the function that maps the hazard states.

3. MODELS OF STATISTICAL DISPERSIONS OF QUALITIES, MAXIMAL PHENOMENA, SEISMIC EMISSION

The rock mass fracturing is a physical phenomenon which is not liable to direct observations. Fractures are caused by vibrations which get distributed in the rock in the form of seismic emission. The registered emission signals are the basis to reason, with the use of a reverse problem, about the fracturing process. The registration of seismic emission is done by means of sensors properly located in the rock mass. The seismic phenomenon is determined by a set of registered signals coming from the same source. That is why seismic phenomena project particular fractures. The sizes of the fractures are measured by the energy of corresponding seismic phenomena, while occurrence times are identified with the time when a given phenomenon starts to be registered. Both fracture times and their sizes are random quantities of determined statistical dispersions. The objective of the investigation is an analysis conducted with respect of the phenomenon size development, i.e. fractures caused by the state of stresses. In this case the occurring fractures depend on one another in time and form sequences called fracturing processes.

The examination of the fracturing process is based on the analysis of maximal seismic phenomena. Maximal phenomena can be determined in two manners: when the signal coming from the phenomenon is registered on many measuring stands, or directly, based on the signals energy. Maximal phenomena are proper data to reason about the progress of the fracturing process until the rock bursts occur. The assessment of the fractures development is done by analyzing the parameters of statistical dispersion of seismic emission characteristics, i.e. phenomena energy E_k and time intervals between the phenomena u_k. These characteristics, being random variables, are connected by a linear statistical dependence [3] that can be expressed in the following manner:

$$\log \frac{E_k}{E_0} = \alpha \left(\frac{u_k}{u_0} - 1 \right) + \varepsilon_k \qquad (1)$$

where:
α – coefficient,
E_k and u_k – implementations of random variables, i.e. values which adopt the described characteristics,
E_0 and u_0 – reference values,
ε_k – random deviations.

The statistics show [14] that in this case the statistical dispersions of these characteristics are described by the same model. The fracturing process is homogeneous when the statistical dispersion of emission characteristics is described by one-parameter exponential function [1]:

$$F(\zeta) = \begin{cases} 0 & dla \quad \zeta_k < 0 \\ 1 - \exp\left[-\beta^{-1} \zeta_k \right] & dla \quad \zeta_k \geq 0 \end{cases} \qquad (2)$$

where:
ζ_k – values taken by a random variable, in the case of energy

$$\zeta_k = \log \frac{E_k}{E_0},$$

in the case of time intervals:

$$\zeta_k = \frac{u_k}{u_0} - 1,$$

E_k – phenomena energy values,
u_k – time interval between successive phenomena,
E_0 and u_0 – reference values.

For higher values of stresses we can observe increasing trends in the sizes of fractures [10]. This way the time intervals between the phenomena grow. As a result of that, the fracturing processes are heterogeneous. In practice, the heterogeneity effect is expressed by a situation when statistical dispersions of the discussed qualities depend on several parameters. Such processes are called doubly stochastic Poisson processes or Cox processes [11]. In the case of seismic emission the statistical dispersions of the discussed characteristics are described by the Weibull model [13], [1]:

$$F(\zeta) = \begin{cases} 0 & dla \quad \zeta_k < 0 \\ 1 - \exp\left[-\lambda^{-1} \cdot \zeta_k^{\gamma} \right] & dla \quad \zeta_k \geq 0 \end{cases} \qquad (3)$$

where:
λ and γ – parameters, however $\lambda > 0$, $\gamma > 0$, in the case of phenomena energy the parameter $\gamma \geq 1$ while in the case of time intervals between phenomena $0 < \gamma \leq 1$, other symbols as above.

When the parameter $\gamma = 1$, the model describes the probability distribution of the qualities of the homogenous stream of events (2). It shows that the parameter γ can be a criterion which enables to detect the growing component $\{\gamma_t\}$ of the stream of events. The expected value $M[\zeta] = m_\zeta$ of seismic emission features is expressed in the following manner:

$$m_\zeta = \lambda^{\gamma^{-1}} \gamma^{-1} \cdot \Gamma\left(\gamma^{-1}\right) \qquad (4)$$

where:
$\Gamma(\bullet)$ is a gamma function.

Finally, it is important to note that statistical dispersions of both discussed features of seismic emission are described by the Weibull model (3).

4. FUNCTION DESCRIBING THE PROGRESS OF ROCK BURST HAZARD, MODELLED BY HAZARD PARAMETERS

Analyzing the rock mass fracturing processes it is possible to assess the trends of their development as far as their increasing sizes and, simultaneously, increasing values of the phenomena energy are concerned. Having this in mind, the authors worked out a model of a function describing the rock burst hazard development process. The value of the function is assigned to the given time interval *T*, the so called information window. In order to calculate the function, it is necessary to determine certain functionals provided that the energy of the phenomena in the window *T* exceeds the set threshold level Q_E. The procedure is similar to that of the seismic hazard method: what is assessed is the functional which determines the probability of the phenomena energy exceeding the Q_E threshold level. In the hazard method, seismology experts call this probability "seismic risk" [12], [15]. In the case of the discussed seismic emission the knowledge about the statistical dispersion (3) enables to determine this probability assigned to the window *T* in the following form [3]:

$$R(Q_E, T) = 1 - \exp[-N(Q_E, T)] \tag{5}$$

where:
N – is a number of all maximal phenomena included in the window *T*, while $N[Q_E,T]$ – is a number of phenomena whose energy exceeds that of the threshold value Q_E.

The number of phenomena whose energy exceeds that of the threshold value Q_E can be expressed as follows:

$$N(Q_E, T) = N[1 - F(Q_E)] \tag{6}$$

where:
$F(Q_E)$ – is the probability described by the model (3).

In practice, it is very useful to apply the functional which determines the expected value of the number of seismic phenomena $M[Q_E,T]$ which exceed the level Q_E, i.e.:

$$M(Q_E, T) = R(Q_E, T) \cdot N(Q_E, T) \tag{7}$$

The function describing the rock burst hazard process, marked $FW_t(Q_E,T)$, was defined in the form of the product $M_t[Q_E,T]$, described by the dependency (7), and by the component $\hat{N}t$ (*T*) which represents the expected value of the number of all maximal phenomena registered in the window *T*.

$$FW_t(Q_E, T) = M_t(Q_E, T) \cdot \hat{N}_t(T) \tag{8}$$

The $\hat{N}t$ (*T*) component is estimated based on time intervals between the phenomena ($\zeta = U$), dividing the size of the window *T* by the expected value m_u described by dependency (4) – then we obtain the following:

$$\hat{N}(T) = \frac{T}{\Gamma(\hat{\gamma}^{-1})} \hat{\gamma} \cdot \hat{\lambda}^{-\frac{1}{\hat{\gamma}}} \tag{9}$$

where variables with hats are estimators of parameters λ and γ, determined on the basis of time intervals between the phenomena included in the window *T*.

The above quantities are estimated in the moving information window *T* with step *d*, achieving the function variability waveform (8) dependent on time $FW_t(Q_E,T)$. This function is sampled evenly with the step *d*. The time t is a real time determined as a moment of the right edge of the window *T*, so all phenomena included in the window *T* have occurrence times smaller than t. In comparison with the classic definition in the form of probability $R_t[Q_E,T]$, the function (8) is characterized by significantly higher resolution. This is caused by the component $M_t[Q_E,T]$, which increases monotonically for the increasing values of the argument, much faster than the probability $R_t[Q_E,T]$. The second component of this function, $\hat{N}t$ (*T*), representing the emission activity in the window, describes its drop caused by a stop in the rock mass movements and preceding the moments of rock bursts.

It is sound to say that statistical analysis of the values of seismic-acoustic emission maximal phenomena with the use of the hazard method enables to identify processes which happen in the period preceding the moments of rock bursts. These processes are the following: increasing volume of the phenomena and the effect of stopping the movements in the rock mass. Figures (1) and (2) feature the waveforms of the discussed function $FW_t(Q_E,T)$, estimated based on seismic emission registered by means of a seismic-acoustic system.

In Fig. 1 it is possible to see that the moment of the rock burst t_{ws} occurs after the function maximum. It means that the rock burst caused the rock mass relaxation, while the function values dropped to the background level. This is classic behaviour of a function describing rock burst hazards.

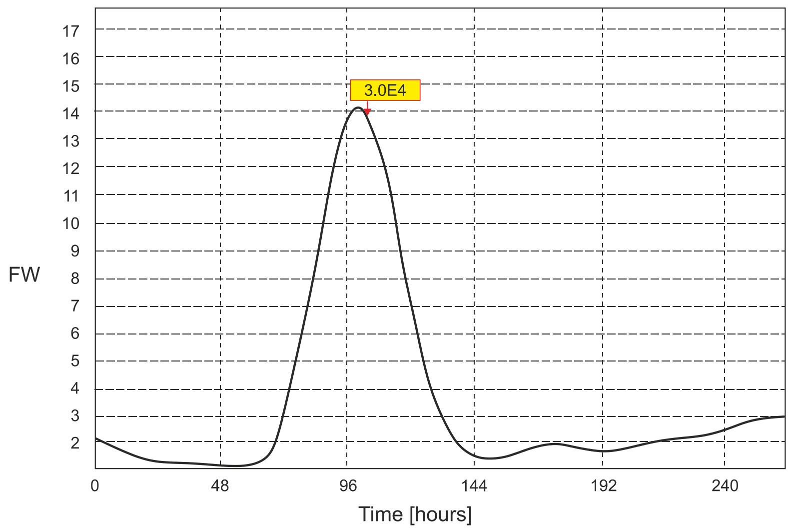

Fig. 1 Waveform of risk function $FW_t(Q_E,T)$ illustrating a situation when the moment of rock burst t_{ws} occurs after the function maximum

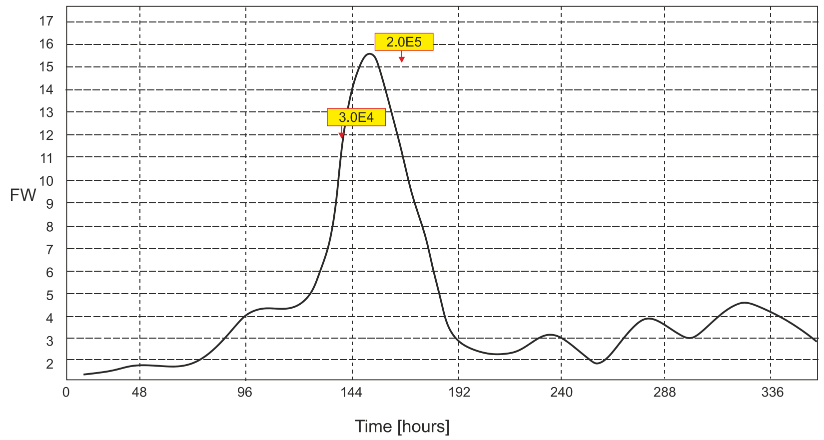

Fig. 2 Waveform of risk function $FW_t(Q_E,T)$ illustrating a situation when the moment of rock burst t_{ws} occurs before the function maximum

Figure 2 features a situation when the rock burst moment t_{ws} occurs before the function maximum. The situation happens when a rock burst with relatively low energy does not cause rock mass relaxation and the function values keep on increasing It is not until a high-energy rock burst occurs after the function maximum, that there is rock mass relaxation and its drop to the background level. Finally, it is necessary to explain that, contrary to "seismic risk" which is a global term in seismology, the term of "function risk" is local and is a real-time function.

5. CONCLUSIONS

The objective of the article is to present possibilities to assess the rock burst moment. The assessment is conducted on the basis of a risk function which describes the rock burst hazard. The issue is solved with the use of the hazard method which is based on a statistical analysis of the energy of seismic emission maximal phenomena, i.e. the phenomena of maximal energy. The analysis of the hazard is carried out on the basis of data collected from time intervals (windows) of several hours. The authors presented a model of a function describing the rock burst hazard process in real time. The function is described by means of the hazard parameters which are determined on the condition that the energy of seismic phenomena exceeds the assumed threshold level. Its values increase monotonically along with the increase of stresses. This shows that the moments of rock bursts occur after the function maxima, provided that the bursts cause the rock mass relaxation. In the case of increasing values of stresses, the function has an increasing waveform until the fracturing process is finished. This moment can be interpreted as a time of the rock burst occurrence, on the condition that the burst caused the stresses to drop to the level below the value of the rocks critical strength. The moment always occurs after the function maximum. However, there may be cases when the bursts occur before the function maximum. It happens when the bursts do not cause the rock mass relaxation and the values of stresses keep on increasing along with the values of the hazard function. Such situations were depicted in Fig. (1) and (2), which feature examples illustrating the risk function waveform. The results presented in this article show, in compliance with Fig. (1) and (2), that the hazard begins to increase from over a dozen to several dozen hours before the moment of the rock burst. After the rock burst causes relaxation, the hazard drops to the background level within a few hours and the next burst will not happen until the risk function increases again. This assumption is confirmed by many researchers in such works as: [3], [4], [5], [6], [7], [14], and [8]. The moment of the rock burst is a random variable and its value, with certain probability, is included in the confidence interval. Thus, the interval between the maximum time and the rock burst moment depends on the confidence interval and the window size. Based on the deliberations presented in the article, one can conclude that reliable assessment of rock burst hazard and the actual moments of rock bursts is possible only on the basis of the analysis of low-energy seismic emission, registered in the INGEO system.

Finally, it is important to note that research within this range should be continued as it contributes to better work safety and uninterrupted exploitation. In addition, based on the analysis of the risk function waveform it is possible to assess the volume of waiting time after the burst.

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