The forecast of mining-induced seismicity and the consequent risk of damage to the excavation in the area of seismic event

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Objective
The Central Mining Institute has developed a method for forecasting the amount of seismic energy created by tremors induced by mining operations. The results of geophysical measurements of S wave velocity anomalies in a rock mass or the results of analytic calculations of the values of pressure on the horizon of the elastic layers are used in the process of calculating the energy. The calculation program which has been developed and adopted has been modified over recent years and it now enables not only the prediction of the energy of dynamic phenomena induced by mining but also the forecasting of the devastating range of seismic shock. The results obtained from this calculation, usually presented in a more readable graphic form, are useful for the macroscopic evaluation of locations that are potential sources of seismic energy. Forecasting of the maximum energy of seismic shock without prior knowledge of the location of the shock’s source, does not allow shock attenuation that results from, for example, a distance of tremor source from the excavation which will be affected by seismic energy, to be taken into consideration. The phenomena of energy dissipation, which is taken into account in the forecasts, create a new quality of assessment of threat to the excavation. The paper presents the principle of a method of forecasting the seismic energy of a shock and the risk of damage to the excavation as a result of the impact of its energy wave. The solution assumes that the source of the energy shock is a resilient layer in which the sum of the gravitational stresses, resulting from natural disturbances and those induced by the conducted or planned mining exploitation, is estimated. The proposed solution assumes a spherical model for the tremor source, for which seismic energy is forecasted as a function of the longwall advance and the elementary value of seismic energy destroying the excavation. Subsequently, the following are calculated for the forecast of the seismic energy of a shock with the defined location of its source: value of the coefficient of dispersion/attenuation of seismic energy and the flux of seismic energy at predetermined distances from the tremor source. The proposed solution for forecasting the seismic energy of tremors and the level of risk of damage to the excavation during the functioning of mining operations is helpful in the development of bump prevention. Changing the intensity of mining operations enables the level of the seismic energy induced by the operations both at the stage of its development and during the excavation of a seam using the longwall method to be controlled. The presented solution has been produced for an area disturbed by the mining of coal seam 510 in the hard coal mine, Jas-Mos. An original program developed by CMI was used for the calculations.

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1. Introduction
Carboniferous rock mass is built of sedimentary rocks. It is characterized by clearly defined limits of petrographic changes (Liszkowski & Stochlik, 1977) that allow elastic layers capable of accumulating energy as a result of undermining interference to be distinguished. The range of the rock mass disturbance in the direction of the surface is greatest in the case of exploitation with a longwall system with caving. However, in cases of other exploitation systems, the rock mass and the layers forming it are subject to displacements and deformations usually on a smaller scale and with lower intensity. In the case of the multi-seam extraction of a deposit, the level of rock mass disturbance will be a result of its disturbance with successive exploitations, regardless of the systems applied. This points to the need to analyse all the progress of exploitation

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2300-3960/© 2017 Central Mining Institute in Katowice. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
achievements in the area of the carried out or planned mining operations to assess the causes of static and dynamic events.

The existing or driven mining excavations have finite resistance to the static and dynamic impact of surrounding rocks. In the first case, the balance between the pressure of rocks on the support and its load bearing capacity will assure the functionality of excavations. In the second case, maintaining the load capacity of the support is a more complex issue.

Physico-mechanical properties of carboniferous rocks are highly diversified. Nevertheless, for the dynamic phenomena provoked by mining activity, those rocks which are characterized by high physico-mechanical parameters combined with forces of primary cohesion are essential. The differences in their deformability determine the formation of discontinuities in the roof, including discontinuities ahead of the longwall face (Drzewiecki, 2004). The range of rock mass disturbance results from the depth of exploitation, the mining system, the advance as well as the severity of the rock mass disturbance due to past mining exploitation. The actual dimensions of disturbed rock mass covers a series of excavations, including active workings. Especially, the active workings, due to the processes of destruction of rock mass in their vicinity cause its weakening, which leads to periodic instability. This process is finite for the completed exploitation range (Drzewiecki, 2015).

Mining practices prove that the vast majority of dynamic phenomena induced by mining operations are located relatively close to the mining site, (Mutke, Lurka, & Dubinski, 2009; Stec, 2015).

With regard to the dynamic issues resulting from mining activities, the role of the energy stored in the rock mass at a given moment of time and for a given level of disturbance gains prominence. In the area of the rock mass, where mining-induced changes occur in the form of layers, the energy, as part of the dynamic events, should be estimated for the entire volume of the disturbed rock mass. This means that each newly generated discontinuity in the rock mass will change the state of deformation and displacement of all the layers. The creation of a new discontinuity in the area of mining activity impact causes a change in the energy accumulated there to an extent that corresponds with the new equilibrium state. Therefore, the energy which will be emitted from such an area is not only the energy that accompanies the formation of a new discontinuity, but it is also represents the difference in the energy stored there before and after the deformation. Propagation of an existing discontinuity or creation of a new one results in a change in the system of forces keeping the rock mass in balance. The consequence of the new balance of forces is the rock mass striving to obtain re-equilibrium state, accompanied by movement and seismic phenomena.

Strong seismic events in the area of the longwall panel length are particularly significant from the point of view of safety. Discontinuities determined by exploitation, either parallel or perpendicular to the bedding, are the source of shocks. The size and range of discontinuities formed in the area of the longwall panel length depends on the longwall front advance. For a given exploitation advance, the range of dynamically created discontinuities according to the bedding direction can be described by a set of parabolic curves (Drzewiecki, 2004). In cases when the section of mining excavation is located within the range of the dynamic impact of the process of crevices formation, the risk of damage to or destruction of the excavation depends on the seismic energy and its distance from the energy source.

The calculation program developed by CMI allows seismic energy that may be radiated from the area of the greatest concentration of stresses to be forecasted and an estimation of the range of areas with a given probability of excavation destruction as a result of the dynamic impact of shocks to be made (Drzewiecki & Iwaszenko, 2008).

2. Material and methods

2.1. Recorded seismicity

The exploitation area of longwall no. 24 in seam 510 is monitored by a Multilok seismic network comprised of 28 seismometers. The exploitation area of longwall 24 in seam 519 is monitored by a Multilok network comprised of 28 seismometers. The accuracy of a focal model, to a large extent, depends on accurately determined tremor focus. The events, located by the mine’s staff using the MULTILOK software exhibit uncertainties in the epicentral coordinates to the extent of ±50 m, which are much smaller than the uncertainty in depth determination of over 100 m. This is because the location of seismometers is mainly at the level of coal seams. The MULTILOK software for tremor location is able to select one of the following minimization algorithms: Simplex, the modified Powell algorithm, and the Davidson-Fletcher-Powell algorithm (Lurka, 1996).

Above the area of the conducted exploitation, there are five measurement stands whose position in relation to the exploited seam is shown in Fig. 1. Seismic phenomena occurred during the excavation of longwall 24 in seam 510 and the amount and level of tremor energy increased during the operations in the impact area of the residues from seam 502. In the period from 5/3/2016 to 6/29/2016, 36 tremors of seismic energy $10^3$ J were recorded, seven tremors with seismic energy of $10^4$ J and one event of $10^5$ J. These are shown in Fig. 2. In particular, the $10^5$ J tremor was strongly felt in the longwall gate although it did not cause rock burst. This fact has determined the need to verify the forecast of tremor energy, the probable location of its centre and to implement required changes to the bumping prevention.

2.2. Seismicity forecasting

The process of the dynamic stratification of the basic roof of the longwall panel length depends on the size and intensity of its exposure. Transversally isotropic construction of the roof (Podgorski & Kleta, 1980) determines the position of the planes of weakening — isotropy planes at the boundary layers of highly variable mechanical properties. The elastic layer distinguished in the overlying profile, due to the rigidity of the rock mass, mainly accumulates the energy of non-dilatational strain.

![Fig. 1. Location of geophone sensors over the region of the conducted operation, the tremor of energy $4 \times 10^5$ J is marked in red.](image-url)
Changes in mining operation progress affect the energy accumulated which is periodically, together with the propagation or formation of new discontinuities, dispersed in the form of wave energy. It should be emphasized that the coverage area of the rock mass at the longwall panel length, in which the dynamic division of the roof takes place, is variable with changes in the intensity of exploitation.

Depending on the intensity of operations, coverage area is limited by parabolic curves with a range that varies with progress both in the direction of the longwall face and the surface. One consequence of this process is the participation of elastic layers or their lack in accumulating energy, which varies with the advance (Drzewiecki, 2004).

Dynamic phenomena affect the structure of the excavation support, the degree and intensity of these phenomena depend on the distance of the centre of the tremor from the excavation and the energy that reaches it.

The relationships that exist between support and rock mass at the moment of the shock must be considered both in terms of mass-momentum moving in the direction of void/excavation (Drzewiecki, 2002b) and wave energy (Konopko, 1994). In the first case, the stability of the excavation is influenced by its resistance to the dynamic movements of a part of the rock mass, initiated by its movement e.g. within the area of the shock source. The second case should be considered as the assessment of seismic energy that reaches the excavation from the shock hypocentre (Aki & Richards, 1980; Shearer, 2009), compared with the elementary energy that can destroy it (Konopko, 1994). In this case, the participation of seismic energy in the overall energy balance of the process of destroying the structure of the rock medium is decisive. It is characterized by a parameter of seismic efficiency which expresses the ratio of seismic energy to the total energy released in the process of rock mass destruction. Its value varies from per milles to 10 percent depending on, for example, the mechanism of the seismic event source (Gibowicz, 1989; McGarr, Spottiswoode Gay & Ortlepp, 1979).

The program developed in the Central Mining Institute for the calculation of seismic energy which is emitted from the tremor centre assumes the value of this energy at the level of 1% total energy. The accuracy of this seismic efficiency parameter was confirmed by the comparable analysis of the forecasted seismic energy of tremors with the energy recorded in the collieries of the Upper Silesian Coal Basin between 1996 and 2007. The accuracy of the forecast in relation to the seismic phenomena with energy of $1.0 \times 10^5$ J to $1.0 \times 10^6$ J is confirmed in 70% of cases and from $1.0 \times 10^6$ to $1.0 \times 10^7$ in 86% of cases (Piernikarczyk & Drzewiecki, 2008).

The mining and geological conditions around longwall 24 in seam 510 of the colliery “Jas-Mos” indicate that the areas where stresses in the elastic layers of the roof are affected by the operations are of interest for the determination of the areas in which seismic phenomena may occur. Stress concentration in the analysed region stems from the depth of the seam deposition, faults occurring at its edges and exploitation residue from seams 505/1 and 505/2.

These areas accumulate energy. However, depending on the distance over the excavated seam, their range varies with the intensity of mining operations and range will include two distinct sandstone layers (Fig. 3).

Determining which horizons and parts of sandstone undergo mining-induced deformation which accumulate the greatest deformation energy requires taking into account the kinematic parameter of the main impact range $\tan \beta_{km}$, which varies with the advance (Drzewiecki, 2002a). For the analysed bed of sandstone and for the average actual advance of exploitation $= 3$ m/day $\tan \beta_{km} = 0.37$ for the first bed of sandstone and $\tan \beta_{km} = 0.46$ for the other.

According to mining practice, a sandstone bank is not monolithic and it is possible to distinguish privileged layers, weakened
layers or reinforced layers in its section, in relation to the direction of the exploitation deformation. They are planes of isotropy, thus they can be regarded as a bed of sandstone and the rock mass can be regarded as a transversally isotropic body (Podgorski & Kleta, 1980).

The adopted ET program allows us to specify the value of energy stored in the sandstone layers and the seismic energy that can be emitted from it, for different values of exploitation intensity that disturb the rock mass.

The program includes calculations for any division of the sandstone layer along isotropic planes.

It is known from practice that the minimum thickness of a deformed elastic layer that can emit energy that is dangerous to a mining crew does not exceed 2.5 m (Drzewiecki, 2004).

For this study the minimum thickness of sandstone that is capable of storing energy was assumed to be 5 m. The calculations have been carried out for the following parameters characterizing the exploitation of seam 510 and the distinguished beds of sandstone.

- Depth of seam deposition, 800 m;
- Daily longwall advance, 3 m;
- Modulus of sandstone elasticity, $E_s$ 7000 MPa;
- Geometric parameters of the 1st bed of sandstone; the thickness $= 21$ m, the distance from the roof of seam 510, 10 m;
- Geometrical parameters of the 2nd layer of sandstone; thickness $= 33$ m, the distance from the roof of seam 510, 39 m.

3. Results and discussion

In the first calculation cycle concerning: for what thickness of the sandstone layer seismic energy of the tremor be greatest at the time of the cracking of the layer. At this stage of the calculations, the sandstone banks are divided into 2, then 3, then 4 etc. Layers of equal thickness. It has been assumed that the minimum layer thickness is greater than 5 m. For each division of the sandstone, the program calculates the potential seismic energy that can be emitted from each layer which has been separated as a result of cracking. The set of results obtained is presented graphically to facilitate the analysis and enables the selection of a layer and its location in relation to the excavated seam, which may potentially emit the greatest amount of seismic energy.

Fig. 4 shows an exemplary application window of the ET program, in which the results of seismic energy as a function of mining advance for each of the four layers separated from one bed of sandstone are presented in the form of curves.

The results show that for an exploitation advance of 3 m/day from the first bed of sandstone, a layer with a thickness of 5.25 m, deposited 10 m above the seam, is a potential source of seismic energy of $1.9 \times 10^6$ J. The other sandstone bed with a thickness of about 33 m, deposited 39 m above the seam, due to its distance, may emit maximum seismic energy of $1.2 \times 10^6$ J irrespective of the multiplicity of its stratification into layers.

In the next step of the calculation, using the ET program, the seismic energy was calculated for the selected layers of sandstone: a spherical model of the source, the damping coefficient of destructive seismic energy $\lambda$ – i.e. a numerical value determined for the seismic energy, expressing reduction in the amount of energy in the vicinity of the excavation in relation to the energy released in the hypocentre (Konopko, 1994). In the course of research, the program calculates the time-averaged flow of seismic energy $S_{dr}$ reaching an excavation from a bursting layer and resulting from the integration of transverse and longitudinal waves which are emitted from a tremor source. It is also another way of presenting the reduction of seismic energy reaching the excavation. For the assumed probability of the risk of damage to the excavation, the

**Fig. 4.** The main application window of the ET program.
program calculates the limit distance $r$ from the hypocenter tremor to the excavation fulfilling the adopted probability of the risk of its destruction (Drzewiecki, 2009).

For the operating conditions of longwall 24 in seam 510, with a daily advance of about 3 m, the results of the calculations are shown in Figs. 5 and 6.

From the point of view of work safety, apart from the maximum energy that can be emitted from the undermined beds of sandstone, their devastating impact on the excavations is significant. As indicated in Figs. 5 and 6, for this set of exploitation parameters, the destructive distance $r$ in which there is a 90% level of certainty of a tremor occurrence, is in the range of approximately from 19 m to 23 m. This also means that the destructive distance $r$ will be variable in a function of the adopted probability of destruction, as shown in Fig. 7. This figure also shows the variability of the destructive distance $r$ of a tremor as a function of the probability of excavation destruction and the distance of the beds from the seam for both beds of sandstone. It should be emphasized that the 2nd bed of sandstone, deposited 39 m above the seam being a source of seismic energy of $1.2 \times 10^{6}$ J and seismic events located directly above the excavation have a 65% or lower probability of excavation destruction. Whereas, the 1st bed, deposited 10 m above the seam, which is the source of shocks with their hypocenters located at a distance of less than 23 m from coal seam and with maximum predicted seismic energy of $1.9 \times 10^{6}$ J will cause excavation’s destruction or permanent damage.

4. Conclusions

The paper presents the results of calculations and comparative analyses of the forecasting of seismic energy of shocks induced by mining activities, aimed at promoting the method developed by GIG and used successfully since the end of the 20th century. As shown in this paper, using the example of longwall 25 in mining seam 510 in the Jas-Mos mine, this method enables the estimation of the risk of damage to the excavation as a result of high energy seismic event. The forecast of the maximum seismic energy of a shock without giving the position of the layer which is the source of the shock does not allow attenuation resulting, for example, from a distance of the shock source from the excavation, which will be affected by seismic energy, to be considered.

Taking energy dissipation into account in the forecasts creates a new quality assessment of the risk of destroying an excavation.

This paper presents the principle of a method of forecasting the seismic energy of the shock and the risk of damage to the excavation as a result of the impact of wave energy. The solution assumes that the source of the seismic energy event is a resilient layer, in which the sum of the gravitational stresses resulting from natural disturbances and stress induced by the conducted or planned mining exploitation is estimated.

The proposed solution assumes a spherical model of the tremor centre, for which the seismic energy in the function of the longwall progress and the elemental value of the seismic energy that destroys the excavation are forecasted.

Subsequently, for the forecast of shock seismic energy with a defined source position produced, the following are calculated: the coefficient $\lambda$ of dispersion/attenuation of seismic energy and the flux of seismic energy at predetermined distances $r$ from the tremor source. The obtained results are presented in graphic form due to their readability. They are useful for the macroscopic evaluation of the position of areas that are potential sources of seismic energy.

The forecast of the maximum seismic energy which may be expected during mining operations, and in particular the forecast of its source and location of tremor centres induced by mining operations for different intensity of exploitation determine the level of the threat of the excavation’s destruction.

Knowledge of these elements enables the level of seismic energy induced by exploitation, both at the stage of its planning and during seam mining with longwall system, to be “controlled”.

The proposed forecast of a seismic event’s energy and the risk of destruction to the excavation, resulting from its impact, is helpful in the development of passive and active rock burst prevention. At the same time, it represents the possibility to introduce necessary changes in mining technology, i.e. a periodic change in exploitation advance, active and passive prevention measures or the location of safe workstations for a given level of exploitation.

Fig. 5. Curves of energy variation, damping coefficient of destructive seismic energy $\lambda$, the stream of seismic energy $S_{dr}$ reaching the excavation, and limit destructive distance $r$ of seismic event source from the excavation for the assumed probability of its destruction at the level of 90% – 1st bed of sandstone.
Fig. 6. Curves of variation of energy, damping coefficient of destructive seismic energy λ, the stream of seismic energy $S_n$ reaching the excavation, and limit destructive distance $r$ of tremor source from the excavation for the assumed probability of its destruction at the level of 90% – 2nd bed of sandstone.

Fig. 7. Variability of the destructive range $r$ of seismic shock as a function of the probability of the excavation destruction.

References


