GOSPODARKA SUROWCAMI MINERALNYMI

Tom 25 2009 Zeszyt 3

HENRYK MARCAK*

Inverse problems in modelling mining shocks

Introduction

Mining shocks occur during the exploitation of underground seams in many mines in Poland. Describing the mechanisms of seismic energy relaxation and attempting to find away of quantifying seismic risk have been the subjects of many scientific works.

The most important questions for mining geophysicists dealing with seismic measurements in mines are to do with the prediction of strong seismic events under specific mining and geological conditions. This issue may be described as a forward problem.

It is possible to predict the distribution of elastic stresses and the deformations in specific geological and mining situations related to them. A mining shock, however, is an inelastic phenomenon. Changes in the physical properties of rock masses resulting from the development of stresses preceding a rock burst cannot be uniquely characterized.

1. The bifurcation model

This model describes the sliding of rock masses as a result of differences between static and dynamic friction forces. This model does not, however, predict sliding if two or more surfaces are considered (Turcotte, Schubert 2002).

Let two masses, m_1 and m_2, move on a surface against friction forces F_1 and F_2 pushed along a path with constant velocity, V, by two springs with the elastic coefficients k_1 and k_2.

The masses are connected by a spring with elastic coefficient kc. The equilibrium of the elastic forces is described by the equations:

* Professor Eng., AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Cracow.

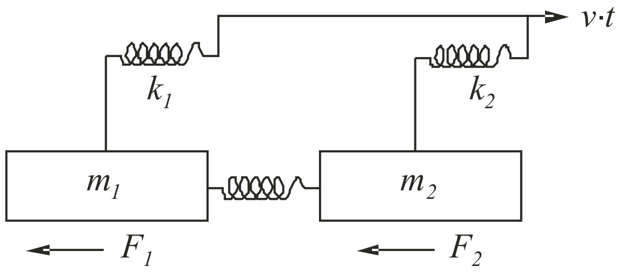

Fig. 1. Model of moving masses on the friction surface

Rys. 1. Model przemieszczania mas na powierzchni tarcia

$$k_1 y_1 + k_c (y_1 - y_2) = F_{s1}$$
$$k_2 y_2 + k_c (y_2 - y_1) = F_{s2} \tag{1}$$

where:

y_1, y_2 are the displacement of masses m_1 and m_2 and
F_{s1}, F_{s2} are the static friction forces.

The dynamic equilibrium is described by the equations:

$$m_1 \frac{d^2 y_1}{dt^2} + k_1 y_1 + k_c (y_1 - y_2) = F_{d1}$$
$$m_2 \frac{d^2 y_2}{dt^2} + k_2 y_2 + k_c (y_2 - y_1) = F_{d2} \tag{2}$$

where:

F_{d1}, F_{d2} are the dynamic friction forces.

It can be shown (Turcotte, Schubert 2008) that assuming $m_1 = m_2$, $k_1 = k_2 = k$, $\tau = \frac{t}{m}$, $\frac{F_{S1}}{F_{D1}} = \frac{F_{S2}}{F_{D2}} = \phi$, $\alpha = \frac{k_c}{k}$, $\beta = \frac{F_{S2}}{F_{S1}}$, $Y_1 = \frac{y_1}{F_1}$, $Y_2 = \frac{y_2}{F_1}$.

These equations can be transformed as below:

$$\frac{d^2}{d\tau^2}(Y_1 - Y_2) + (2\alpha + 1)(Y1 - Y2) = \frac{1}{\phi}(1 - \beta) \tag{3}$$

The solution of this equation gives the bifurcation points. It can be shown that small changes in the values of the parameters ϕ and β in the equation (3) can produce large changes in the resulting displacements y_1 or y_2.

From the observed similarity between the displacement of masses in this model and seismicity in mining areas it can be concluded that stresses may be released in different ways (for example, as a number of mean-energetic events or as a single strong event) and that the time and energy of these events cannot be predicted due to the nature of this process.

2. The dynamic development of deformations before a strong shock

2.1. Inverse models of mining shocks

Inverse models are often considered in geology (Tarantola 1987). The solution to the inverse problem describes the conditions under which the observed geological phenomenon occurs. In the case of mining shocks, solving the inverse problem is a matter of specifying the physical conditions in a rock mass that exist before a release of seismic energy.

Recognizing the dynamic conditions and changes in the physical properties in an area preceding a strong seismic event are necessary for solving the inverse problem. It would appear that an interpretation of the measurement of seismic events in mines is more fruitful in the context of the inverse problem than the forward problem.

The inelastic deformations that precede a strong shock develop in a several stages. The following stages can be seen as necessary but not sufficient conditions for the occurrence of a shock but, on the other hand, the appearance of each stage does increase the probability of the occurrence of a seismic event.

Geophysical methods can be used to recognize these stages of seismic development. The following stages can be distinguished.

Roof layer splitting

Zorychta's paper (2002) analyses the distribution of stresses around a typical copper mining operation in Poland's Lower Silesia region. In this paper it is shown that shear stresses reach their maximum values in two narrow zones perpendicular to the borders of excavation. These shear stresses can cause plastic deformations of litologic borders or the splitting of roof layers. This process can be detected using extended measuring systems in boreholes in roof layers (Orzepowski 1998; Matwiejeszyn, Ptak 2002) or with geophysical seismological and seismoacoustical equipment (Marcak 1992). Marcak's paper (Marcak 1992) shows that continuous plastic deformations of a roof layer result in the formation of "tranche zones" in that layer. "Tranche zones" are zones of intensive cracking and fracturing. The results of this cracking and fracturing may be detected in seismologic and seismoacustic mining measurements. The distances between "tranche zones" (zones of intensive inelastic deformations in the roof layers of exploited areas), depend on the geometric and mechanical properties of the layers in question. The occurrence of "tranche zones" causes the development of block structures, and sliding between these blocks, in the roof of an exploited area, and these result in an increase in the stresses on the exploited seam. One consequence of this is that plastic deformation can be expected in the base of these rock blocks. This fact has important consequences, in particular the rotation of the direction of the principal stresses (Marcak 2002) and potential sliding between surfaces that are inclined to the principal stresses by an angle of $\frac{\pi}{2} - \partial$, where ∂ is the angle of internal friction. When a potential sliding surface has the same angle as the surface of discontinuity in a roof beam, sliding along this surface and extension becomes more probable.

The appearance of the surface of discontinuity

The deformation of roof layers can be affected by inhomogeneities in their structure. 'Inhomogeneities' in this context include fractures, faults, weak zones, and zones with strong stress gradients. The development of stresses resulting from roof beam splitting and bending produce horizontal tensile and compression stresses related to the bending curvature – whether it is positive or negative. According to geomechanical theory (Jager, Cook 1971) the stresses in a beam at y_0 distance from its central line is described by the formula:

$$\delta = \frac{E \cdot y_0}{R} \tag{4}$$

where R is the beam's bending curvature, and E-Yang modules.

The strong horizontal stresses that are produced result in bending. With a positive curvature R the tensile stresses δ_y can produce splitting in the top surface of the roof block when it reaches the value:

$$\delta_y = (\beta_0 + \beta_z \delta_z) \tag{5}$$

where:

β_0 is cohesion,
β_z is the coefficient of internal friction,
δ_z is the stress perpendicular to the splitting surface.

The block is formed with the sliding surface on its internal border and the conditions on this surface can determine the occurrence of seismic shocks.

2.2. The dynamics of inelastic deformations on the surfaces of discontinuities

Each fracture is the result of the occurrence of a surface of discontinuity and the surfaces through which the stresses are acting (Fig. 2). The ratio of these surfaces is an essential

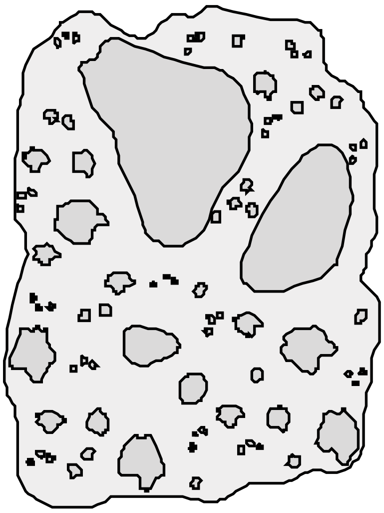

Fig. 2. Distribution of in homogeneity of the rock strength on seismic surface

Rys. 2. Rozkład niejednorodności wytrzymałości na powierzchni sejsmicznej

parameter in determining the occurrence of shocks. Asperities and "bridges" form contacts at a surface of discontinuity. At the level of asperity contact a local force-deformation relationship determines elastic deformation and inelastic sliding. If the opening of a fracture is large enough, the inelastic energy realized during sliding cannot produce a seismic shock. The effective stiffness of a rough contact is related to the force-deformation behaviour of asperity contacts and statistical descriptions of rock-joint surface topography.

The stiffness of asperities and the distribution functions of asperity heights and contact orientations can be used to derive the stress-deformation relationship for a rock joint.

It must be expected that most cases of real sliding are associated with seismic relaxation. The crushing of asperities (Marcak 2008) makes it impossible to close them tightly and tightly closed asperities are necessary for a seismic event. However, in very stiff rocks, the closing of asperities can occur if the normal force on the discontinuity surface is large enough and if the distribution of asperities allows it. This can result in a seismic energy release.

The distribution of asperities on the surface of a discontinuity is shown in Figure 2. This distribution depends on the history of the geological strata (faults, fractures, long-lasting stress gradients, and corrosion). A seismic shock may be the result of sliding in one of the elements shown in Figure 2 (a weak event), in several of them (a mean event), or on a part of the surface (a strong event). The energy of seismic events and their location also depends on the value and distribution of normal forces in relation to the sliding surface.

The value of these stresses depend on the depth of the exploitation (an increase in depth causes an increase in all elements of stress tensor), the height of the exploitation (an increase in height produces an increase in dragging force resulting in roof-beam bending), and the rate of advance of the exploitation (an increase in the rate of advance causes rapid plastic deformations). The distribution of normal stresses also depends on the stage of rock-mass

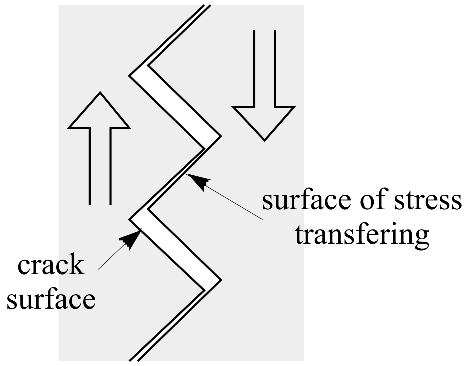

Fig. 3. The surface of crack and the surface by which the stresses be transferred

Rys. 3. Powierzchnia pęknięcia i powierzchnia, przez którą przenoszone są naprężenia

deformation. The initial plastic deformations on the bottom surface of a roof block results in the rotation of that block. The upper part of the block is squeezed and the sliding of the block leads to an increase in seismicity in the upper part of the layer. Bending of the layer transforms the stress distribution so that seismicity can be expected from the top part of the layer instead.

The location of a surface of discontinuity can, of course, be situated at a location other than the area in which the stresses of direct exploitation are present (around faults for example). However, the inhomogenity of stresses, particularly the occurrence of an area in which asperities are closed, must occur.

The redistribution of stresses resulting from the release of seismic energy very often leads to the extension of a potential sliding surface and increases the risk of the occurrence of a strong seismic event.

2.3. The conditions under which a strong event may occur

It has been shown (Akai and Richards 1980) that the energy of a seismic event can be modelled by the formula:

$$E = -v\bar{u}\sum \bar{\delta} \tag{6}$$

where:

v is the energetic seismic efficiency,

$\bar{\delta}$ is the the mean stress on the sliding surface,

$\bar{u}$ is the mean displacement.

It can be concluded from this formula that an energetic seismic event will be preceded by the formation of a large sliding surface. Seismic events have a tendency to be located along a linear element (Marcak 1985). Also, the development of sliding surfaces can be interpreted from radar satellite measurements.

The second important element in the development of deformations prior to a seismic event is the tight closing of asperities in the area of the seismic source. The closing of asperities results from the rotation of a rock block by the principal stresses in the system. This is only possible if the asperities are strong enough to allow tight closing. Seismic events can occur in sandstones, limestones, dolomites and sometime in existing faults. Sliding surfaces developed in the area surrounding a mining excavation but it is also possible for deformations to develop outside of an active mining area and for them to be brought into a mining area via self-automata processes (Marcak 2008). This kind of seismic event is difficult to interpret. Estimating the vertical position of the hypocentre is useful in analysing such situations.

3. The geophysical effects of seismic deformation before a seismic event

The solution of the inverse problem shows the advances and limits of the estimation of seismic risk in underground mines on the base of geophysical investigations. Such events cannot be predicted, but it is possible to identify elements of the stages of rock deformation that precede a seismic energy release. Seismic and seismoacoustic measurements can be used to identify plastic deformations in the roof layer of an exploited seam that cause splitting of the roof beam and to estimate the “breaking step.” Seismic measurements can be interpreted in such a way as to identify a potential sliding surface and to follow its development over time. It is necessary to adapt a method of interpreting geophysical data to the size and location of the sliding surface. At the minimum the development of deformations along a surface can be assessed with seismological and seismoacoustic methods (Marcak 1995, 1997, 2002) and with gravimetric methods (Fajklewicz 2007). The seismic method (Shreader 2008) and the radar satellite method (Pilecka 2008) can also be used.

The development of deformations before a seismic event is connected not only with sliding surfaces but also with the source area where the opening and closing of asperities and fractures can be observed. Changes in the physical properties of rocks related to the opening or closing of asperities can be identified using seismic and gravity methods (Dubiński 1989), (Fajklewicz 2007).

It can be concluded that the strategy of assessing seismic risk by solving inverse models is more effective than strategies based on solving the forward problem.

Note: This paper was sponsored by Grant MEiSW nr PBS-Grecja-10-2007

REFERENCES

A l u K., R i c h a r d s P.G., 1980 – Qualitative Seismology. W.H. Freeman and Company, San Francisco, 1–519.

D u b i ń s k i J., 1989 – Sejsmiczna metoda wyprzedzającej oceny zagrożenia wstrząsami górniczymi w kopalniach węgla kamiennego. Prace GIG, seria dodatkowa, Katowice.

Fajklewicz Z., 2007 – Grawimetria stosowana. Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH, Kraków, 424.

Jeager J.C., Cook N.G.W., 1971 – Fundaments of rock mechanics Chapman and Hall L.T.D., 365.

Marcak H., 1985 – Geofizyczne modele procesu destrukcji skał poprzedzające tąpnięcie i wstrząsy w kopalniach podziemnych. Publ. Inst. Geophys. Pol. Acad. Sc. M-6, s. 149–173.

Marcak H., 1992 – Zastosowanie modelu dylatacyjno-plastycznego do oceny stanu zagrożenia tąpaniami. Zesz. Nauk. AGH, s. Geod. Stosowana, z. 9, 39–57.

Marcak H., 1997 – Teoretyczne podstawy badania zagrożeń naturalnych w kopalniach metodami geofizycznymi. Mat. Szk. Ekspl. Podz., CPPGSMiE.

Marcak H., 2002 – The influence of strata and tectonics on the rockburst hisk In Polish mines. Seismogenic Process Monitoring (Ogasarava M.,Yanagidani T., Ando H. eds.). Balkema, Roterdam, 51–61.

Marcak H., 2006 – A Geophysical model for the analysis of seismic emission in the area of rock beam splitting caused by mining operations. International Mining Forum 2006 Ed. Sobczyk and Kicki Taylor and Francis, 73–87.

Marcak H., 2008 – Fizyczne podstawy użycia metod geofizycznych w badaniach naprężeń w skałce. Gospodarka Surowcami Mineralnymi t. 24, z. 2/3, 177–199.

Marcak H., Stopyra J., Damżal J., Wróbel J., 1977 – Zmiany parametrów strefy spękanej w stropie chodnika wykonanego w samodzielnej obudowie kotwiowej. Przegląd Górniczy 5, 7.

Matwiejszyn A., Ptak M., 2002 – Measurements of borehole deformations for assessment of rockburst hazard. Seismogenic Process Monitoring (Ogasavara M., Yanagidani T., Ando M eds.). Balkema, Rotterdam, 30–39.

Orzepowski S., 1998 – Próba określenia ryzyka powstania tąpię na podstawie pomiarów deformacji w pionowych otworach i ich związek z zarejestrowaną sejsmicznością. Materiały XXI Zimowej Szkoły Geomechaniki AGH, 349–367.

Pilecka E., 2008 – Analiza kierunków lineametrów indukowanej na terenie LGOM. Gospodarka Surowcami Mineralnymi t. 24, z. 2/4, 135–146.

Szreder Z., Pilecki J., Kłosiński J., 2008 – Efektywność rozpoznania oddziaływań krawędzi eksploatacyjnych metodami tłumienia oraz prędkości fali sejsmicznej. Gospodarka Surowcami Mineralnymi t. 24, z. 2/3, 215–227.

Tarantale A., 1987 – Inverse problem theory. Elsevier, Amsterdam, 320.

Turcotte D.L., Schubert G., 2002 – Geodynamics. Cambridge University Press, 456.

Zorychta A., 2002 – Tąpnięcia jako zjawiska utraty stateczności skał otaczających wyrobisko. Geomechaniczne modele górotworu tąpiącego. Bibl. Szkol. Ekspl. Podz. IGSMiE PAN.

INVERSE PROBLEMS IN MODELLING MINING SHOCKS

Key words

Geophysical measurements, seismic discontinous surfaces, miozofractivies closing, seismic migration

Abstract

The polish mining industry confronts a number of obstacles. One of these is the necessity to reach deep layers in both coal and underground copper mines. One of the consequences of this deep mining activity is the need to cope with the high risk of rock bursts. Associated risks to the health and life of miners must be considered. Geophysical methods are used to identify deformation processes in rock masses prior to seismic events. Due to the complexity of the problem of analyzing the movements of rock masses that produce seismic shocks it is often concluded that predicting mining shocks is impossible. An analogy of the problem can be constructed by considering the movement of two masses, linked to a moving frame and each other by springs, on a surface with friction. The masses are analogous to rock masses and the surface to a discontinuity along which they are moving producing seismic shocks. Analysing this model leads to the conclusion that predicting mining shocks is impossible. However, by examining the conditions under which shocks occur, it turns out that geophysical measurements can be used to identify the inelastic deformation processes in rock masses that precede strong mining shocks. It can be shown that the deformations occurring before strong mining shocks have several stages, including splitting in the roof an exploited seam (the roof layer), the occurrence and development of sliding planes in the seismic zone (zone of seismic migration), the tightening of micro-fractures and cracks in the volume of the future seismic source and, the final stage, a seismic release of energy. The development of seismic inelastic deformations cause changes in the physical properties of rock-masses as well as changes in seismic emissions. Both of these can be recorded using geophysical measurement systems. The correct interpretation of geophysical measurements recorded in underground mines can lead to better identification of the stages of inelastic deformation that precede seismic shocks.

ZAGADNIENIA ODWROTNE W MODELOWANIU WSTRZĄSÓW GÓRNICZYCH

Słowa kluczowe

Pomiary geofizyczne, sejsmiczne powierzchnie nieciągłości, zaciskanie mikropęknięć, migracja sejsmiczna

Streszczenie

Współczesny przemysł górniczy w Polsce jest ograniczony wieloma przeszkodami. Jedną z nich jest konieczność eksploatacji urobku z dużych głębokości, zarówno w kopalnictwie węglowym jak i rudnym. Konsekwencją tej sytuacji jest między innymi konieczność podejmowania eksploatacji w warunkach zagrożenia tąpaniami. Tąpnięcia niosą ze sobą duże ryzyko utraty zdrowia, a nawet życia górników. Powodują jednocześnie istotne perturbacje w procesie wydobywczym i są związane z dużymi stratami ekonomicznymi. Istniejące metody geofizyczne pozwalają śledzić proces deformacji poprzedzającej tąpnięcie, a w konsekwencji oceniać ryzyko jego powstania. Nie jest to jednak zadanie proste. Analogia pomiędzy ruchem dwóch mas powiązanych z ramą poruszającą się za pomocą sprężyn oraz przesuwaniem mas na dwóch powierzchniach nieciągłości prowadzi do wniosku, że przewidywanie wstrząsów w konkretnej sytuacji górniczej jest niemożliwe. Jeżeli jednak zadamy pytanie, jakie warunki musiały być spełnione aby wstrząs powstał (zadanie odwrotne), to okazuje się, że pomiary geofizyczne mogą spełniać istotną rolę w identyfikacji procesów deformacji niesprężystej w górotworze, które muszą poprzedzać powstanie silnego wstrząsu górniczego. Można wykazać, że silny wstrząs górniczy musi być poprzedzony kilkoma etapami deformacji takimi jak: odspojenie warstwy stropowej, wytworzenie płaszczyzny nieciągłości, rozwój tej strefy i związana z nim migracja sejsmiczna, zaciskanie szczelin w przyszłym obszarze źródłowym wreszcie sejsmiczna relaksacja. Rozwojowi kolejnych etapów deformacji towarzyszą zmiany właściwości fizycznych i zmiany emisji fal sprężystych, które można rejestrować metodami geofizycznymi. Strategia interpretacji wyników pomiarów geofizycznych, której celem jest identyfikacja poszczególnych etapów deformacji poprzedzającej wstrząs sejsmiczny pozwoli lepiej wykorzystać wyniki pomiarów sejsmicznych w kopalniach.