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DESCRIPTION OF INDUCED SEISMICITY LEVEL BASING ON ANALYTICALLY CALCULATED CHANGES OF ELASTIC ENERGY IN ROCK LAYERS SUBJECTED TO DEFORMATION

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ABSTRACT

The paper develops the approach (already presented – Acta Montana – s.A. No.16) where the analytically calculated changes in rockmass involving the distribution of the components of stress (strain) tensor are applied for long-term prediction of seismicity level induced by multi-bed mining. In consequence, the increase (decrease) of the appropriate elastic strain energy is calculated. Also the damage of rocks is investigated. It has been showed that as it is in the case of induced seismicity, these quantities are strongly dependent on the geometry and space-time development of multi-bed mining, and hence, to determine extreme values in their distributions, it is required that effective in terms of calculation three-dimensional – spatial solutions are applied. The results of exemplary analytical solutions, which are based on a relatively simple solution of the shift boundary problem of elasticity theory were presented.

Expressing the relation between the observed seismicity and the analytically calculated changes of elastic energy by means of the linear regression model – for example for the particular headings – we forecast the changes of seismicity level, including the distribution of predicted energy of tremors.

KEYWORDS: seismicity, strees, strain, seismicity prediction

1. INTRODUCTION

The prediction of seismicity, especially the long-term one, induced by mining works, or another words, the estimation of energy release of potential tremors is still a problem open to scientific investigation. Energy release, and in particular maximum energy of the expected tremors induced by mining works is most frequently determined, as it is generally known, using statistical methods (Lasocki S., 1990) adopted from global seismology. It happens when in the area of analyzed extraction a sufficient number of seismic events have been recorded earlier. In spite of the fact that these methods are applied in limited areas of rockmass connected with the progressing mining front, where the generation process of seismic events is not totally of stationary character – it is possible to obtain reliable predictions (Lasocki S., 1996).

The drawback of statistical methods is that during the estimation process, the stress field, strongly changeable in rockmass area and in time, is often neglected. These changes connected with the occurrence of past mining and also effected by the instability of mining parameters (advance, height and length of mining fronts) are allowed for in the analytical approach presented in this work. However, the presented here approach does not allow for the influence of changes in the geological structure of bed on the distribution of stresses and elastic strain energy predicted in rockmass. It seams to be well grounded with long-term seismic predictions to use also the analytical approach, apart the methods based on statistical analysis of events. With this approach (Jaworski A.,1998, 2000) it is necessary to establish correlative relationship between the analytically calculated changes (increase, decrease values) of elastic deformation energy in the deformed, strong rock layers and the observed seismicity.

When we investigate mining works planned in the areas where hitherto no seismic events have been recorded, neither of the mentioned above prognostic approaches applies. In such cases other methods are used, and for example in the Upper Silesia Coal Basin the maximum energy of potential tremors is determined using empirical method (Biliński A., 1992) based on a so called model of disturbed rockmass. This method as well as the one mentioned above does not focus on the run of induction process of mining tremors. It can not be used to define seismic hazard, but it can be applied to predict with sufficient reliability the energy order (10E5J, 10E6J,…) of events.

The discussed analytical description of energy changes involves solely elastic strain energy accumulated in rockmass in effect of disturbing it with a arbitrarily formed mining process; it does not mention anything about its dissipation and transformations, and in consequence it does not determine the amount of energy released in the damaging process of a given rockmass.

In the damaging process of rock medium, this potential elastic strain energy changes into other (Fairhurst C., Cornet F., 1981) types of energy, practically undeterminable in terms of quantity, including kinetic energy of elastic waves associated with seismic energy of the recorded tremors. Therefore, although we are only investigating the changes of potential energy (elastic strain energy) dependent on mining parameters, they are translated into the run of seismic activity, although we do not know to what degree in terms of quantity. Hence, it is reasonable to search for a relationship between the analytically estimated changes of potential energy and seismic energy of tremors – the only measurable, being a convention in fact, form of energy.

In the paper (Jaworski A., 2000) a prediction method of the changes (increase, decrease values) of the specific energy of elastic strain [J/m^3] is presented on the levels of the strong rock layers deformed by mining. A commonly known Clapeyron equation defining elasticity potential as the product of components of stress tensor and strain tensor has been applied. Also an algorithm for the calculation of instantaneous value of this energy in a definite calculation point has been described. For the calculations, the solution of spatial dislocation boundary condition of elastic strain theory has been applied (Gil H., 1991). In line with this algorithm, sequences (tables) are formed, of stress and strain increase values from elementary extractions (unit longwall advance) into which particular mining plots are divided. These sequences are then transformed into sequences of changeable in time values of the components of stress and strain tensors which describe the influence of space-time development of mining and deposition depth.

By means of the applied methodology we can effectively calculate the changes of elastic strain energy in arbitrary time intervals and areas, in the way that ensures that high energy changes, either instantaneous or local, connected with the configuration and time-based run of mining are not disregarded.

In order to ensure sufficient calculation effectiveness, strong idealization of rock medium is required – homogeneous, isotropic linear-elastic medium.

In the local scale, i.e. in a definite mining field, the distribution of seismic energy is variable in heading gangway and strongly determined, which has been confirmed by numerous investigation studies with mining works parameters. In the same way, which is illustrated by the presented tests, also instantaneous analytical values of the calculated potential energy are strongly dependent on these parameters.

The presented calculation tests show that the description of energy changes taking place in the rockmass deformed by the completed or ongoing mining necessitates that spatial solutions (models) are applied and that calculations are done in small time steps. The necessity to simulate the development of multi-bed mining in small time steps is one of the reasons which hinder the effective application of 3-dimensional methods of finite elements.

2. MINING PARAMETERS AND THE CALCULATED CHANGES OF ELASTIC STRAIN ENERGY

Both investigation studies and the obligatory, periodical analyses carried out in coal mines emphasize a strong relationship between seismicity level and so called ‘mining conditions’. It is reflected in the legal regulations involving the principles to be observed when carrying out mining works and in the applied methodology in the estimation of hazard states, tremors and crumps during the works. ‘Mining conditions’ – mining factors are understood principally as all parameters of the ongoing longwall mining, including its space-time run and intensity. These factors include also the state of multibed extraction of the deposit, including for example the location of past mining (old abandoned workings, and edges) with respect to the ongoing mining works.

The above factors (parameters) decide about the movement of rocks forming the rockmass, and consequently about the changes of strain and stress states which bring about the change of potential energy. As it has already been mentioned, the analytical effective description of this energy change dependent on mining parameters is reduced first of all to the calculation of instantaneous values of specific energy of elastic strain ϕ ; [J/m^3] at points $P_{(x,y,z)}$:

$$\phi_{(x,y,z)} = 0{,}5\left(\sigma_x\varepsilon_x + \sigma_y\varepsilon_y + \sigma_z\varepsilon_z + \tau_{xy}\gamma_{xy} + \tau_{yz}\gamma_{yz} + \tau_{zx}\gamma_{zx}\right) \quad (1)$$

where for example:

$\sigma_{z_{(x,y,z)}} = \sigma_{z_{ekspl}} + p_z$; vertical component of stress generated by the completed and ongoing mining - $\sigma_{z_{ekspl}}$ and deposition depth - p_z,

with $\sigma_{z_{ekspl}} = f\left[\left(w_0, a, b\right) = const, x, y, z\right]$ – the form of the complex function which describes the influence from the elementary extraction of the sides 2a x 2b over which the vertical settlement is w_o has been already presented (Jaworski A.,2000),

$\varepsilon_{z_{(x,y,z)}} = \dfrac{1}{2G(1+\nu)}\left[\sigma_z - \nu\left(\sigma_x + \sigma_y\right)\right]$ – linear strain in the direction of axis Z, G – modulus of shape elasticity , ν – Poisson index.

The constants G and ν in the analytical solution are characterizing averaged properties of rockmass (elastic half space) treated as homogeneous medium.

Since the calculations are carried out at the level of strong sandstone layers, which were not singled out in the solution with constants G, ν, therefore for the estimation of their values we use a typical for analytical simulations, comparative course of action.

Thus, as in the case where the correctness of numerical model is tested, these constants are determined by comparing the results of test calculations (comparative prediction) with observation results.

Therefore, for prediction calculations we introduce their substitute, untrue values, with which the results of comparative prediction are closest to the observed in rockmass stresses and deformation influence of the mining process carried out so far .

For example, the value of stress modulus *G* determined in such a way (*G*=1000MPa) is several times lower than the one determined in the laboratory. Assumed values of the other properties were: ν=0.15, γ=0.025 MN/m³, excavation coefficient a=0.8.

In order to test the ratio of effective stress to rock strength of the rocks deformed by mining, the created matrix of time variable components $\sigma_x, \sigma_y, \sigma_z ...$ of stress tensor are transformed into the matrix of main stress values $\sigma_1 > \sigma_2 \geq \sigma_3$.

The information if and at which stage of mining process the strength of rock around the point P(x,y,z) has been exceeded is provided by the ratio of effective stress σ_0 to rock strength - W. For W≥1 we can say that the strength has been exceeded. The value of this index can be determined using a commonly known in rockmass mechanic linearized form of strength hypothesis of Burzyński, which formulates the measure of failure as the energy of non-dilatational strain and certain part of dilatational strain. The ratio W for the sandstones deformed by mining is determined with a modified hypothesis of Coulomb-Mohr:

$$W_{(x,y,z)} = \frac{\sigma_1}{R_c} - \frac{\sigma_3}{R_r} \quad \text{for} \quad \sigma_3 < R_r$$

$$W_{(x,y,z)} = \frac{\sigma_3}{R_r} \quad \text{for} \quad \sigma_3 \geq R_r \tag{2}$$

This condition allows for the fact that the tensile strength R_r of rocks is considerably lower than their compressive strength R_c. The above strength criterion does not take into consideration many important properties of the rock layer, for example structural defects, which induces us to the application of empirical criteria as well. In analytical simulations we apply the empirical strength criterion of Hoek-Brown (Hoek E., Brown E.T., 1988):

$$\frac{\sigma_1}{R_c} = \frac{\sigma_3}{R_c} + \left(m\frac{\sigma_3}{R_c} + 1 \right)^{\frac{1}{2}} \tag{3}$$

The constant m for Upper Silesia sandstones was determined by strength tests (Kwaśniewski M., 2002). Strenght of the sandstones could be assumed R_c=60 MPa, R_r=6 MPa.

The calculated (1) changes of instantaneous values ϕ_i of elastic strain energy are the results of the work of deformation expressed as the product of forces (stresses σ,τ) and corresponding to them movements/dislocations (strains ε,γ), with the following being determined at calculation points:

- $\Delta\phi_i = \phi_{i+1} - \phi_i$ – the increment of elastic strain energy in 'elementary' time intervals Δt_i, in which the increase values of stresses and strains are defined.
- $\sum_{i=1}^{n} \Delta\phi_i$ - the increment of elastic strain energy for the investigated areas of mining in time intervals $\Delta T = n\Delta t_i$.

Within the area of rockmass undisturbed by mining, in a specific unit volume of deposit (around the calculation point) the density of elastic strain energy calculated in this way as the sum of specific energy of dilatational and non-dilatational strains will be constant and dependent on depth H:

$$\phi_0 = \frac{1-2\nu}{4G(1-\nu)} p_z^2 ;$$

$$p_z = -\gamma H = \frac{1-\nu}{\nu} p_x = \frac{1-\nu}{\nu} p_y \tag{4}$$

At the depth 1000m this density of potential energy of elastic strain $(\phi_0 = const)$ will reach the order of 10^5J/m³. In the reaction area of past mining this energy will be also dependent on the location of the investigated point with respect to abandoned workings and the completed mining edges and will be constant $(\phi_z = const)$, if we neglect the relaxation of stresses. Taking into consideration, due to the observed drop of reaction intensity of past mining in time, the relaxation of stresses – this energy will be dependent on time $(\phi_z = \phi_{z(t)})$.

At the calculation point within the influence of the ongoing mining, the instantaneous energy ϕ_i will be equal to the energy ϕ_0 or ϕ_z increased or decreased by certain value, dependent on the parameters of this mining. The instantaneous energy around the investigated point will be varying in time, so the increment $\Delta\phi$ of the elastic strain energy for a definite advance of mining front will be undergoing changes, dependent mainly on mining parameters.

The changes of instantaneous values of elastic strain energy in the calculation point as dependent on its location with respect to the advancing mining front S1 and past mining (longwalls S2 and S3 extracted earlier) are illustrated by the results of calculation tests – Figures 2 to 5.

Furthermore, for the point located on the symmetry axis of the longwall we present, for the sake of comparison, the run of these changes in coplanar system – the system in which the stresses and strains were determined is working in the coplanar strain state (variant 2D-fig.5). The diagram of mining situation assumed for in the calculation test is presented in Fig.1, with points P_0, P_1 and P_2 being located 40 meters over the field of longwall S1 of the width 200m and length 1000m, driven at the height of 4m with 24h advance of 3m. Longwall S2 was selected in the seam deposited 80m above the longwall S3.

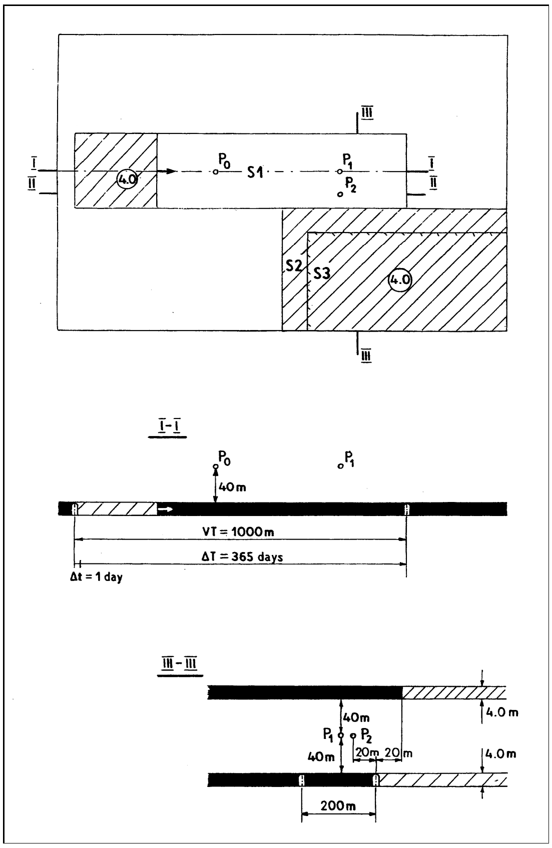

Fig. 1 Scheme of mining situations investigated during the test calculations.

The following was calculated during the simulation (denotations on Fig.2, illustrating the changes of energy around the point P_0 located over the center of longwall field beyond the influence of past mining):

$\Delta\phi_i$ – the increment of specific elastic strain energy in unit time intervals Δt (steps of mining front advance),

ϕ_i – instantaneous values of energy for successive steps of mining front advance,

$\phi_{M(\Delta T)}$ – Maximum value of energy in the investigated time interval ΔT=nΔt, for the mining carried out in time interval ΔT,

$\Delta\phi_{M(\Delta T)}$ – maximum increment of energy in time interval ΔT,

$\sum\Delta\phi_i^+$ - sum of positive increments of energy in time interval ΔT,

$\sum\Delta\phi_i^-$ - sum of negative increments of energy in time interval ΔT,

ϕ_p – initial value of elastic strain energy before the investigated mining was carried out – beyond the influence of mining $\phi_p = \phi_0$ but within the influence of past mining $\phi_p = \phi_z$,

ϕ_k – final value of elastic strain energy after the completion of the investigated mining $\phi_k = \phi_0$ or $\phi_k = \phi_z$ as dependent on the location of the point with respect to past mining (mining already completed).

The test results show high variability of instantaneous values of potential energy in the time period when the rockmass in the vicinity of calculation point is within the influence of advancing mining front. We can also observe the variability of instantaneous values of energy and of other determined quantities as dependent on the location of the point with respect to the past mining. Therefore, when calculating the changes of energy, and in particular if they are to be comparable with strongly variable induced seismicity in the local scale, it is imperative that, apart from the application of spatial solutions, these changes are analyzed in short time intervals. Too large calculation steps simulating the space-time run of mining result in the situation where the extreme values, both on the increase side and decrease side, are neglected.

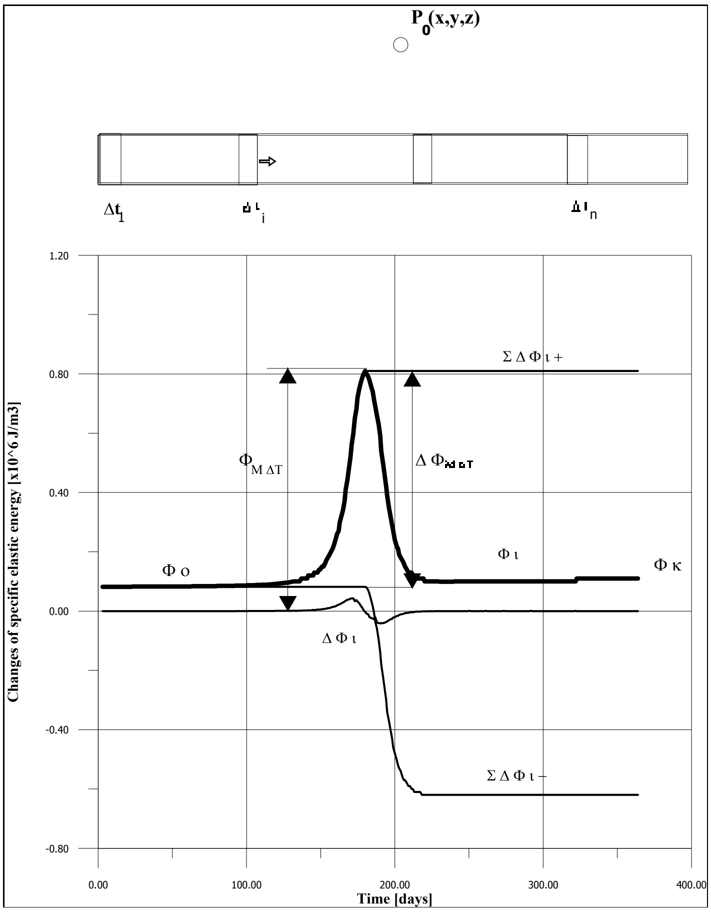

Fig. 2 Changes of specific elastic energy - point P_0, placed on the line of symmetry of the longwall – beyond the influence of past mining works.

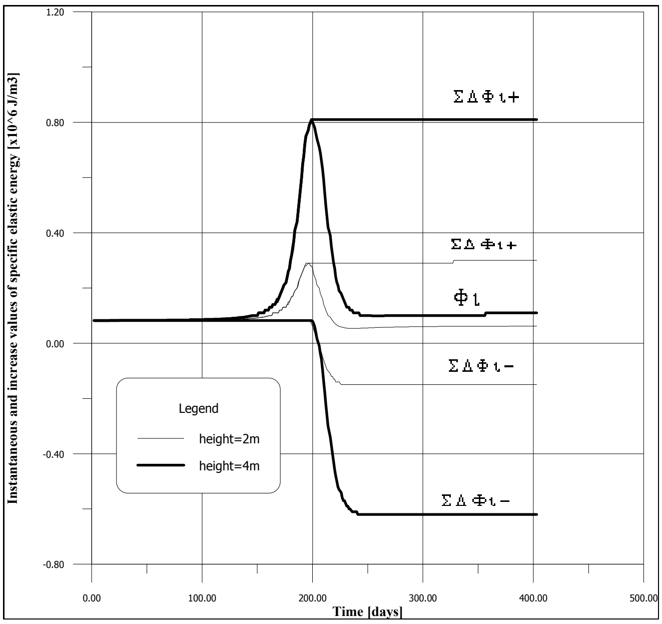

Fig. 3 Instantaneous and increase values of specific elastic energy - point P_0 for different height of excavation

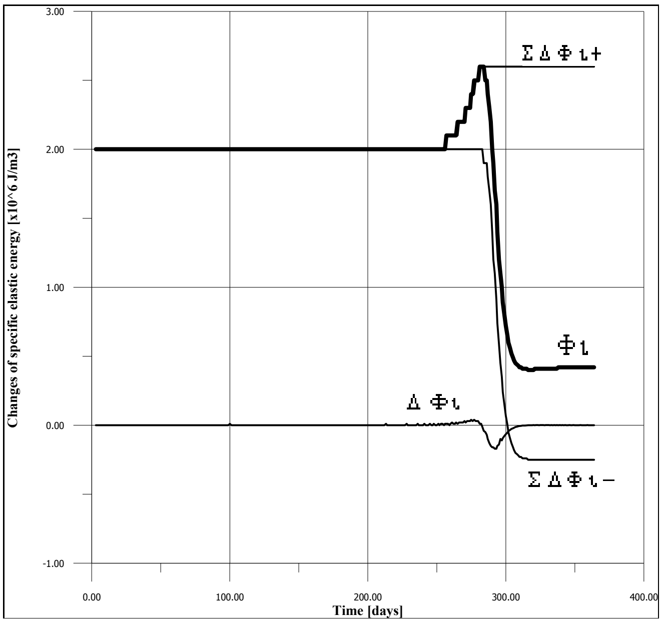

Fig. 4 Changes of specific elastic energy - point P_2, not placed on the line of symmetry of the longwall.

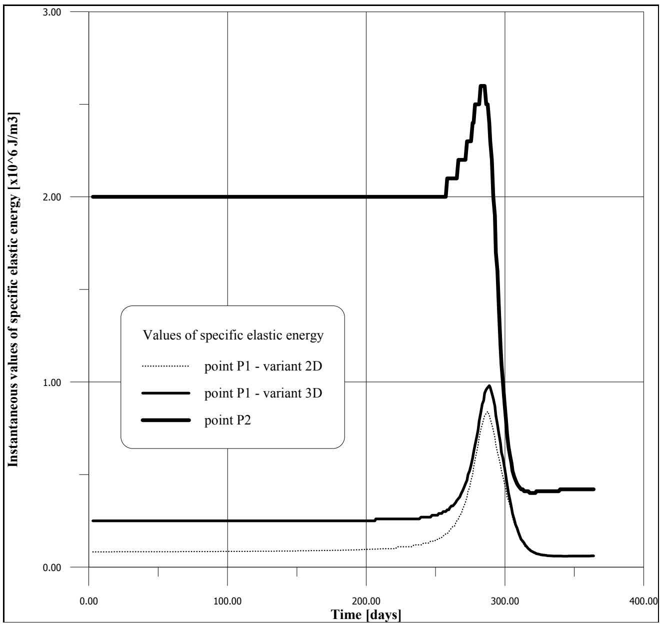

Fig. 5 Instantaneous values ϕ_i of specific elastic energy for examined points.

3. DESCRIPTION OF SEISMICITY LEVEL INDUCED BY MINING

Quantitative description of the run of stress-and-deformation processes and energy changes connected with dynamic damage done to some volume of rocks with respect to such a complex, non-homogeneous medium as rockmass is an open question.

Therefore searching for the relationship between the analytically calculated, with the idealization of true rockmass, changes of potential energy and the measureable (conventionally) seismic energy (quantities dependent on the parameters of mining works) with respect to various practical applications is real only if appropriate regression models are constructed.

In the hitherto carried out investigation studies, the seismicity observed in successive mining development stages was respectively compared with analytically calculated at points P(x,y,z) positive increment $\Delta\phi^{+}$ and negative decrement $\Delta\phi^{-}$ of the specific elastic strain energy in unit time intervals Δt_i (steps of longwall advance) and in longer time intervals $\Delta T=n\Delta t_i$ (sections of heading gangway of longwalls). It results from the fact that this energy, including also its determinable part, i.e. seismic energy of tremors, is released both during the loading and unloading/relief of the rock layer being deformed. Both processes are taking place with different intensity. They depend among others on the instantaneous position of the point (a definite mass of rocks) with respect to the mining front, on the parameters of this ongoing mining and on the structure of past mining.

The tests (Figs. 4 and 5) show that even with a relatively simple system of longwalls (Fig.1), the energy state will not be determined solely by the calculated $\Delta\phi^{+}$ and $\Delta\phi^{-}$ values of elastic strain energy. Since, depending on the location of the calculation point P(x,y,z) and the investigated time period ΔT, the increments of energy $\Delta\phi$ may be low, and the instantaneous values of energy ϕ_i may be high. It will take place when for example the initial energy ϕ_p ; $\left(\phi_i = \phi_p\right)$, i.e. the energy at the beginning of the calculation time period ΔT is high due to strong influence of former mining process. And the increment $\Delta\phi$ of the energy generated by the mining phase carried out in time period ΔT may be relatively small due to low influence of the ongoing mining process.

It motivates us to introduce also the calculated values of initial energy ϕ_p to the regression model.

Finally, leaving aside the problem of damage process of rocks, whose effective, quantitative description in rockmass volume is still a problem, we can introduce to the regresission model the calculated values $\Delta\phi$ of energy, dividing them into the ones occurring before- and after the hypothetical damage of rock.

The dissipation of the elastic strain energy accumulated in the sandstones being deformed may run in a different way over the time when the stresses reach critical value (the calculated effort index W≥1) from the time before it (W<1). Fig.6 presents areas under the longwall field S1, as an example for the mining situation as in Fig.1, where the positive value $\Delta\phi^{+}$ of elastic strain energy was taking palce in the conditions - W≥1 (Fig.6a) and where it was taking place with W<1 (Fig.6b).

With the above formulated assumptions the relations between the observed and calculated quantities can be expressed by relatively simple models of linear regression. The first of them is describing this relation in space-time (at points of the calculation net) and can be used to determine areas of increased seismicity (areas of raised energy release of tremors [J/m^3]) induced by mining carried out over longer time period $\Delta T=n\Delta t_i$:

$$\Delta\phi_{obs_{(\Delta T)}} = a_1 \sum_{i=1}^{n} \Delta\phi^{+}_{i\,obl\,(W<1)} + a_2 \sum_{i=1}^{n} \Delta\phi^{-}_{i\,obl\,(W<1)} + a_3 \sum_{i=1}^{n} \Delta\phi^{+}_{i\,obl\,(W\geq1)} + a_4 \sum_{i=1}^{n} \Delta\phi^{-}_{i\,obl\,(W\geq1)} + a_5 \phi_{Pobl} + \varepsilon \qquad (5)$$

where:

$\Delta\phi_{obs_{\Delta T}}$ – seismic energy recorded in time period $\Delta T=n\Delta t_i$ at each of points P,

$\sum_{i=1}^{n}\Delta\phi^{-}_{iobl}$, $\sum_{i=1}^{n}\Delta\phi^{+}_{iobl}$ - sums negative and positive increments of elastic strain energy, analytically calculated for each of the points of calculation net,

ϕ_{Pobl} - initial (for the beginning of time period ΔT) value of instantaneous energy ϕ_i analytically calculated for each of the points of the calculation net,

n – number of time intervals Δt_i – unit steps of mining front advance ,

$\Delta T=n\Delta t_i$ – comparative calculation time period for which regression parameters are determined,

ε - random component,

a_1, a_2, a_3, a_4, a_5 – parameters of regression model .

The second model is describing this relation in the function of time (in particular time intervals Δt_i) and can be used for the prediction of maximum energy of tremors in particular phases of mining development:

$$\Delta\phi_{obs_{(\Delta t_i)}} = S_j a_1 \sum_{l=1}^{l_{pkt}} \Delta\phi^{+}_{l\,obl\,(W<1)} + S_j a_2 \sum_{l=1}^{l_{pkt}} \Delta\phi^{-}_{l\,obl\,(W<1)} + S_j a_3 \sum_{l=1}^{l_{pkt}} \Delta\phi^{+}_{l\,obl\,(W\geq1)} + S_j a_4 \sum_{l=1}^{l_{pkt}} \Delta\phi^{-}_{l\,obl\,(W\geq1)} + S_j a_5 \sum_{l=1}^{l_{pkt}} \phi_{Pobl} + \varepsilon \qquad (6)$$

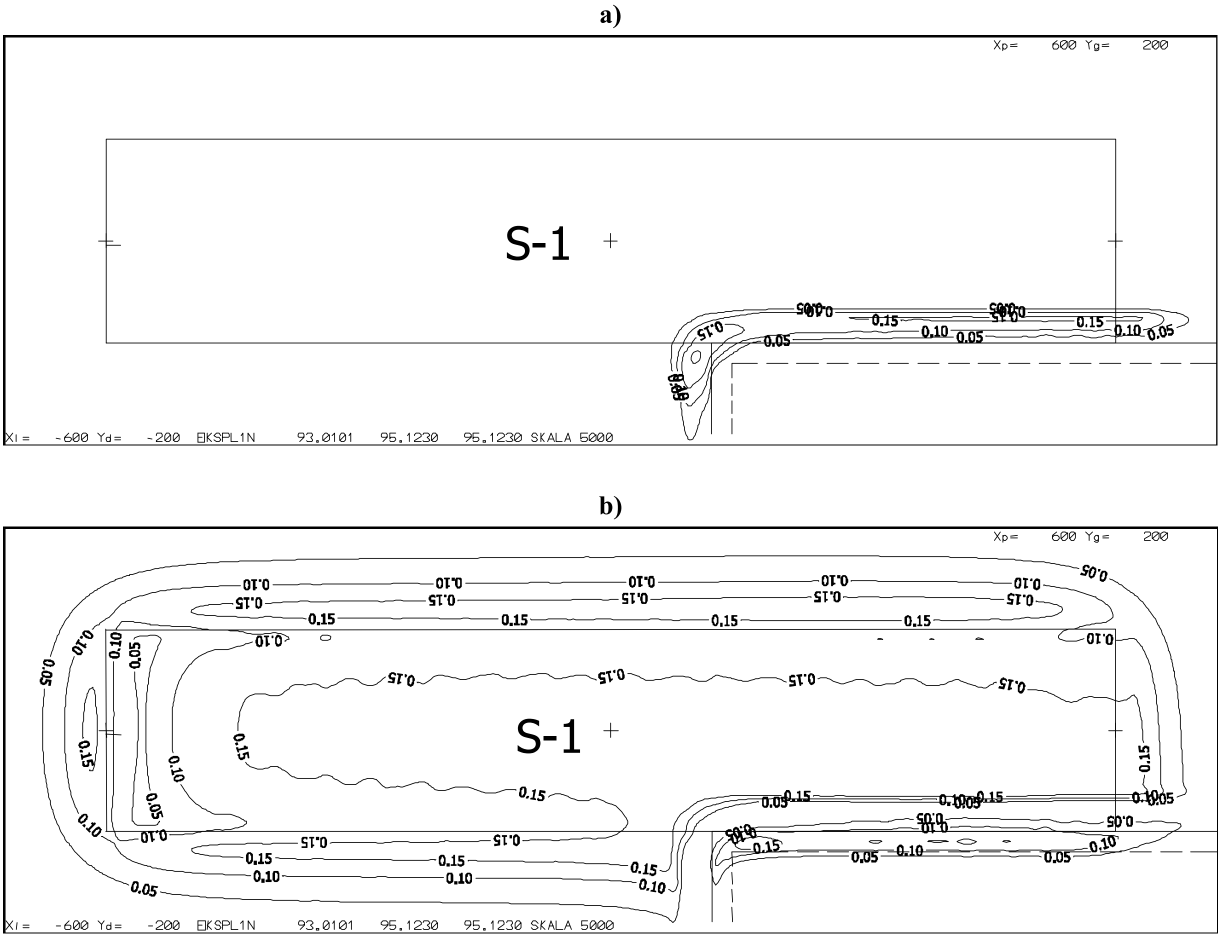

Fig. 6 Increase values $\Delta\phi$ of elastic srain energy over the field of longwall S1, a) In the area where hypothetically sandstone was broken - W≥1, b) In the area where hypothetically the sandstone was not broken -W<1.

where:

$\Delta\phi_{obs(\Delta t_i)}$ - seismic energy observed in unit time interval Δt_i in the analyzed area ('collected' from points P),

$\Delta\phi_{l\,obl}$ - calculated in point „l" increments of specific elastic strain energy in time intervals $\Delta t_i = \Delta T/n$,

$\phi_{P\,obl}$ - initial (for the beginning of unit time interval Δt_i) value of instantaneous energy ϕ_i analytically calculated for each of the points of the calculation net,

n - number of unit time intervals,

l_{pkt} - number of calculation points ,

S_j - unit field, equal to the product of modules of the calculations points net along the line X and Y.

Regression coefficients were determined using the least squares method, according to which the expression below was minimized

$$\sum_{i=1}^{lp}(\Delta\phi_{obs\,i} - \Delta\phi_{prog\,i})^2 \qquad (7)$$

where:

$\Delta\phi_{obs\,i}$ - seismic energy, maximum energy, number of tremors observed at "i-th" point or in "i-th" time interval,

$\Delta\phi_{prog\,i}$ - seismic energy, maximum energy, number of tremors predicted at "i-th" point or in "i-th" time interval,

lp - number of observations (number of calculation points, number of unit time intervals).

To verify the adequacy of the accepted model, each time a number of analyses are carried out to determine whether the model is correct in view of the available data on the run of mining process and recorded seismic energy.

The congruence level involving the distribution of predicted values with the analogous distribution of observed values confirms that it is well grounded to carry out an advance prediction in the investigated mining area, basing on the determined regression indexes.

An advance prediction must be preceded by a comparative prediction.

For example, by calculating analytically the increase values of specific elastic strain energy in the layers of sandstone being deformed and by comparing them with the recorded seismicity. Comparative prediction was carried out, in line with the accepted methodology, involving the distribution of maximum energy of tremors [J] in the function of time – Fig.8.

The comparative prediction calculations involve the area of fall-of-roof longwall M-8 driven in seam 703 in the area of rockmass subjected to the influence of past mining in this seam, as well as the seams 626/2 and 624 deposited about 240 and 340m above. The longwall M-8 is a successive, fifth longwall extracted in the discussed part of the seam. The results of seismological observations show, that, apart from the ongoing mining, the run of seismicity is influenced by the created structure of past mining. Within the driving period of longwall M-8, there were over 3300 tremors, but only the events of the energy from 10^3J to 10^6J were localized, (Fig.7), and whose summary energy was $5.7x10^7$J.

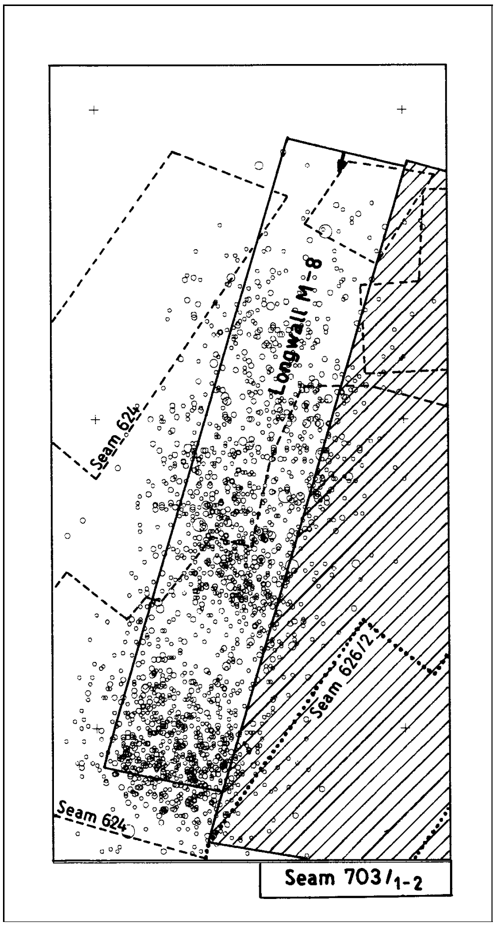

Fig. 7 Mining in seams 703/1-2, 626/2 and 624 with marked tremor foci.

In the tables 1 and 2 the results involving the estimation of model parameters were presented.

- The investigated index – seismic energy release.

Standard deviation of the residual component (prediction accuracy basing on regression function) is 2.34.

Coefficient of correlation R = 0.76, R^2 = 0.58.

The carried out distribution analysis of residual variables has showed that the assumption claimimg the normality of the distribution of residual variables can be accepted as satisfied (points on the diagram lie approximately along the straight line).

Also the analysis involving residual variables in the function of time as well as predicted values did not raise questions involving the adequacy of the accepted model.

- The investigated index - maximum energy of tremors in particular phases of mining development.

Standard deviation of the residual component (prediction accuracy basing on regression function) is 0.63. Coefficient of correlation R=0.92, R^2 = 0.85.

The carried out distribution analysis of residual variables has showed that the assumption claimimg the normality of the distribution of residual variables can be accepted as satisfied. Also the analysis involving residual variables in the function of time as well as predicted values did not raise questions involving the adequacy of the accepted models.

Figure 8 presents the distributions of the observed and comparatively predicted maximum energy of induced tremors during the driving of longwall M-8, basing on the relation (6).

The results of the tests show that in spite of the simplicity of the accepted regression model there is evident correlation relationship between the analytically predicted increase of specific elastic strain energy and the true energy release of tremors.

4. SUMMARY

Making use of computer programs available at present (Białek J., Bańka P., Jaworski A., 1999) as well as calculation capabilities of computers we can effectively make predictions involving the changes of potential elastic strain energy in rock layers being deformed with practically arbitral structure of the completed, ongoing or planned mining process.

High calculation efficiency required when determining the components of stress and strain tensor in large area of rockmass for successive 'unit' steps of the completed and planned mining process is obtained at the cost of strong idealization of the medium (CHILE – continuous, homogeneous, isotropic and linearly elastic).

And therefore, a typical comparative approach of prediction is required (previous predictions were effected by means of calculation tests for a respective range of the already completed mining) in order to

Table 1 Estimation results of regression model parameters - investigated index - seismic energy release – (equation 5).

Parameter	Estimated value of parameter	Standard error	Significance level*
a_1	194.69	20.15	under 0.000001
a_2	-173.21	13.16	under 0.000001
a_3	66.44	13.00	under 0.000001
a_4	-39.06	15.00	0.009356
a_5	1.55	1.58	0.327016

* The hypothesis assuming that a given regression coefficient is equal to zero was tested. The values provided in the Table 1 define the significance level at which this hypothesis should be rejected in favour of the alternative hypothesis $a_i \neq 0$.

Table 2 Estimation results of regression model parameters - investigated index – maximum energy of tremors in particular phases of mining development (equation 6).

Parameter	Estimated value of parameter	Standard error	Significance level*
a_1	76.69	14.96	0.000002
a_2	-29.35	8.34	0.000667
a_3	20.24	3.37	under 0.000001
a_4	-34.84	6.30	under 0.000001
a_5	0.009	0.003	0.008219

* The hypothesis assuming that a given regression coefficient is equal to zero was tested. The values provided in the Table 2 define the significance level at which this hypothesis should be rejected in favour of the alternative hypothesis $a_i \neq 0$.

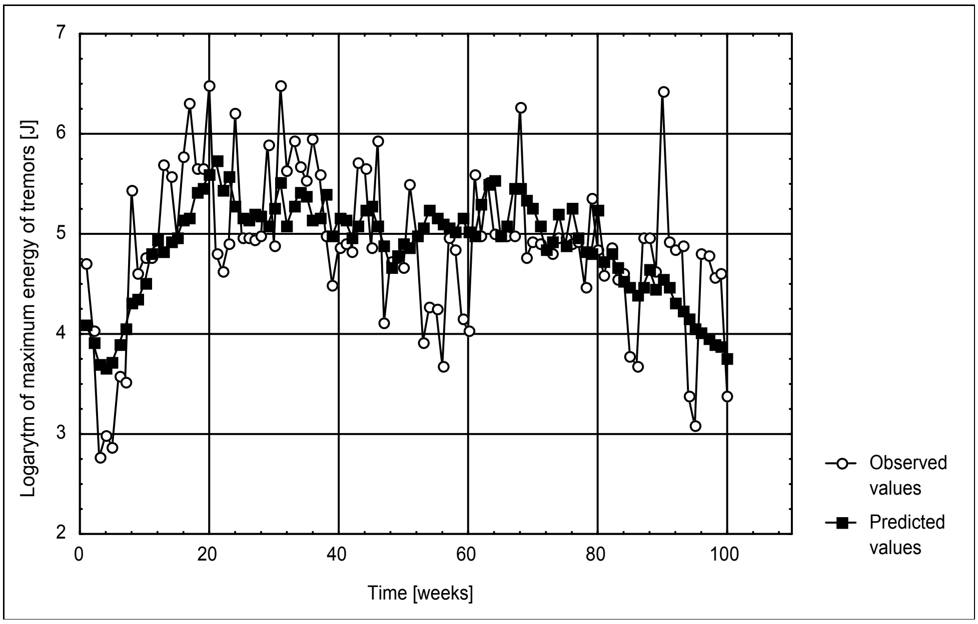

Fig. 8 Distribution of observed and predicted maximum energy of tremors induced in the vicinity of longwall M-8

determine the parameters characterizing the properties of rockmass. These are such values with which the results of the test are the closest to reality – i.e. observation results. When treating the medium as discontinuous, unhomogeneous, anisotropic and non-lineanaryelastic – DIANE, we need to build a big and complex numerical model and to know the strain properties of rock layers placed far away from mining headings. It is also necessary to repeat several times the modeling processes in order to simulate the development of mining process.

The application of a single, simple analytical model (which, unfortunately, does not react to the changes in geological structure of bed) facilitates the comparative analysis of the results of successive predictions.

Analyzing the results of the carried out numerical tests, we can say that the analytically calculated changes of instantaneous values of elastic strain energy as well as other investigated indexes are fully sensitive to the changes of mining condition in which the works are carried out.

By the application of the presented relations between the calculated energy changes of rockmass and the indexes of the observed seismic emission we can effectively estimate the changes in the level of this emission in gangways of the planned longwalls. The changes can be predicted in time-space or in the function of time.

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