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EVALUATION OF ROCKBURST HAZARD UNDER ABANDONED MINE WORKINGS

OCENA MOŻLIWOŚCI WYSTĄPIENIA TĄPNIĘCIA POD ZROBAMI EKSPLOATACJI DOKONANEJ

Recalling the body of experience gathered in the collieries of the Upper Silesian Coal Basin, the increased risk of seismicity and rockburst occurrences in confined conditions including the exploitation of remnants were identified. This study investigates geomechanical aspects of longwall mining in the areas affected by old excavations aimed at relaxation of a multi-bed deposits within a thick coal seam or a group of seams. It is assumed that high-energy seismicity is another factor determining the rockburst hazard alongside the state of stress. A case study is recalled, describing a colliery where mining-induced seismic activity of a de-stressed coal seam remained at the level comparable to or higher than it was experienced in the de-stressed seam operations. An analytical model was used to study the stress state and potential loss of structural continuity of an undisturbed rock body surrounding the longwall panel being mined beneath or over the abandoned workings. Recalling the developed model of the system involving nonlinear functions demonstrating the existence of abandoned mine workings within the rock strata, computer simulations were performed to evaluate the rockburst hazards along the face area. Discussions of results are based on observations of immediate roof convergence and the vertical stress concentration factor at the longwall face zone. Computational data of the modelled mining situations demonstrates that despite using the de-stressing method of mining, the occurrence of events impacting on mine working beneath and over abandoned workings cannot be precluded. Here the scale of rockburst hazards is determined by local mining and geological conditions, such as the type and extent of abandoned workings, their age and vertical distance between them and the coal seam currently mined.

Keywords: mining remnants, confined conditions, rock mass de-stressing, rockburst hazard

Nawiązując do doświadczeń kopalń GZW potwierdzających ogólną tezę o intensyfikacji skali przejawów zagrożenia sejsmicznego i tąpaniami, jakie towarzyszy działalności wydobywczej w warunkach skrępowanych występowaniem zaszłości eksploatacyjnych, w artykule odniesiono się do geomechanicznych aspektów eksploatacji ścianowej w rejonach oddziaływania obszarów zrobów, będących m. in. skutkiem dokonań górniczych ukierunkowanych na odprężenie złoża wielopokładowego w ramach wiązki pokładów lub warstw pokładu grubego. Wychodząc z założenia, że obok stanu naprężeń o wielkości zagrożenia tąpaniami decyduje sejsmiczność wysokoenergetyczna, podano przykład jednej z kopalń węgla kamiennego,

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gdzie parametry aktywności indukowanej eksploatacją pokładu odprężonego kształtowały się na poziomie porównywalnym i wyższym w stosunku do eksploatacji odprężającej. W oparciu o analityczną metodę określania stanu przemieszczenia i naprężenia w otoczeniu elementów ścianowego systemu eksploatacji zaprezentowano rezultaty badań modelowych w zakresie wpływu zrobów na zachowanie się – pod kątem warunków ewentualnej utraty ciągłości struktury – przyprzodkowej partii calizny w pokładzie wybieranym pod/nad zaszłością. Na podstawie opracowanego modelu systemu, w tym indywidualnych funkcji nieliniowych demonstrujących istnienie zrobów w górotworze zrealizowano symulacje komputerowe mające na celu ocenę możliwości wystąpienia tąpnięcia na wybiegu frontu. Dyskusję wyników prowadzono na podstawie obserwacji kształtowania się zmian wielkości ugięcia stropu bezpośredniego oraz współczynnika koncentracji pionowej składowej stanu naprężenia w czole ściany. Dla modelowanych, przykładowych sytuacji górniczych rezultaty obliczeń potwierdziły, iż pomimo występowania efektu odprężenia nie można wykluczyć zdarzenia ze skutkami w wyrobiskach pod/nad zrobami eksploatacji zaszłej, przy czym o wielkości zagrożenia decydują lokalne uwarunkowania geologiczno-górnicze, w tym między innymi rodzaj i rozpiętość zrobów, ich wiek oraz odległość pionowa między zaszłością i pokładem eksploatowanym.

Słowa kluczowe: zaszłości eksploatacyjne, warunki skrępowane, eksploatacja odprężająca, zagrożenie tąpaniami

1. Introduction

Mining operations in coal beds endangered by rockbursts require a variety of correlated preventive measures. The actual long-term and short-term solutions are based on many-years' of expertise in local geological and mining conditions. In rockburst prevention, the forecasting of rockburst hazard conditions is of particular importance. These conditions are mostly based on geophysical methods including seismic and seismo-acoustic observations, seismicity measurements (profiling, X-raying, seismic tomography) and small diameter drilling. In recent years analytical methods have become more popular, particularly when investigating newly-developed mining sections, to identify the range and size of stress concentration zones in the neighbourhood of planned longwall faces or galleries. Underground observations and measurements combined with suitable analytical methods allow a comprehensive assessment of potential changes in rockburst hazard conditions in the regions of mining operations whilst forecasting the maximum energy factor of mining-induced seismicity has now become a standard procedure.

Long-term projects involving the development, first working and cross-cutting of the coal beds, the sequencing of mining operations in terms of time and space, the direction of mining face advancing, mining methods, co-ordination of longwall face and equipment provided in the face and galleries, produce major impacts on surrounding rock strata. The widely adopted strategy to minimise rockburst hazards relies on de-stressing operations defining the sequence of mining activities in the given seams (by overcutting or underholing) and coordinating the mining activities with short-term preventive measures. Of particular importance is clean mining (without leaving any coal residues or pillars) and at the same time minimising the extent of development workings and limiting the intensity of mining operations, particularly over relatively small areas. These aspects are addressed in comprehensive mining plans prepared regularly (every two years) in each mine confronting the rockburst hazards.

In areas where a long-term rockburst prevention strategy cannot be put in place, short-term measures are adopted. These strategies are aimed to weaken the rock strata in the neighbourhood of already identified or prognosticated high stress zones where shock-producing de-stressing blasting and directed fracturing or hydro- fracturing of roof strata and supplying water to undisturbed coal body is implemented. However, rockburst hazards cannot be entirely eliminated mostly due to the age of existing collieries and the level of deposit depletion in their mining areas. Alongside the growing mining depth, each year the geological and mining conditions are becoming more and more complicated.

On account of the specificity of carbonic deposits, mining operations have to be conducted beneath or over mined-out sections and in partly unmined areas. The need to interrupt the mining operations at certain points and sections thus producing residues and pillarsis prompted by local conditions and decisions made are based on such criteria as cost-effectiveness, protection of underground and surface structures, tectonic aspects and natural hazard conditions. Mined-out sections and the remnants of the coal body, also referred to as abandoned mine workings, are the combinations of areas differing in geomechanical properties and behaviour under strain. Depending on the mechanism of their interactions with the rock strata, abandoned workings can be categorised into those in which the stress components are higher than gravity-induced stress state (their main source are unmined seam sections: protective pillars and mining edges) and those in which the stress component tends to decrease (de-stressed areas, mostly the goaf sections). In consideration of rockburst hazards, seismic events during mining operations in de-stressed zones are less likely (Mirek et al., 2016; Bańka et al., 2017) due to the dissipative effects of the goaf areas, yet the occurrence of the fracture zone in the seam section near the face is quite probable from the standpoint of geomechanics and mining practice. Therefore, a rockburst occurrence underneath the abandoned workings in a different coal seam cannot be entirely precluded. Assuming that the necessary condition for a rockburst occurrence is the loss of continuity of the original structure of the strata (Kłeczek et al., 1987; Zorychta, 2003; Goszcz, 2004; Chlebowski, 2013), research efforts are undertaken to identify the critical stress zones in the front section of the mined seam, i.e. in the de-stressed zone, in the context of potential rockburst treated as a process involving the loss of stability in the rock strata.

2. Seismicity and rockburst hazard in a de-stressed coal seam – mining practice

Mining practice and expertise gathered not only in collieries indicates that the actual risk of dynamic events (such as rockbursts) is dependent on the state of stress in the given area and parameters of mining-induced seismicity (Chlebowski et al., 2004; Chlebowski & Burtan, 2007). In general, the influence of the scale of operations, including mining operations undertaken in order to de-stress other seams or thick seam layers is expressed as stress variations in neighbouring rock strata, yet when analysing this influence, two aspects need special consideration. On one hand, mining operations aimed at de-stressing give rise to positive stress changes and hence to changes in elastic strain energy density in overlying and underlying strata; on the other hand the effects are transmitted onto the entire rock medium, encompassing the potentially rockburst-prone features, resulting in an enhanced risk of seismic events. In consideration of the geological profile of the strata, the actual locations of those features within the seams and geotechnical conditions in the area (including the extent of mining activities) should be considered. Beginning mining operations in the de-stressed seam can result in increasing seismic hazard due to the fresh activity of shock-prone strata during the fracturing or breaking. It is a widely established view that major determinants of rockburst hazards include seismic events with the highest energy characterised by close distances from the focus of the event. That is why, despite energy dissipation on the cavings in the de-stressing seam (during overcutting), mining activities can lead to high-energy shocks, making the risk of a potential event comparable to the previously mentioned rockburst hazard levels.

A real example of such occurrence is the situation experienced in one of the collieries in the Upper Silesian Coal Basin during mining of a coal seam divided into two strata (upper stratum – de-stressing, bottom stratum – de-stressed). The mining operations involved 6 longwall faces (4 in the roof stratum, 2 in the floor stratum) with caving-in as the roof management system (KHW S.A., 2014). This case is specific in that seismic activity registered during the longwall working in the two strata, expressed in terms of the amount and energy of events and the energy factor (J/Mg of output) was relatively high (see Table 1), whilst special consideration was given to the de-stressed strata.

TABLE 1

Parameters of mining-induced seismicity

Rock strata	**Longwall face**	**Number of events according to the seismic energy rating**					**SA_s [J]**
		10^3 J	**10^4 J**	**10^5 J**	**10^6 J**	**10^7 J**	
De-stressing (beneath the roof)	0	225	53	5	1	—	$5{,}76\times10^6$
	1J	427	188	45	—	—	$1{,}09\times10^7$
	2J	223	81	7	—	1	$3{,}58\times10^7$
	3J	3590	461	83	13	1	$1{,}28\times10^8$
	Σ	4465	783	140	14	2	$1{,}80\times10^8$
De-stressed (floor stratum)	1Jd	1495	273	20	1	—	$2{,}59\times10^7$
	2Jd	933	302	121	14	2	$2{,}05\times10^8$
	Σ	2428	575	141	15	2	$2{,}31\times10^8$

Among the total number of seismic events (with seismic energy $\geq 10^3$ J) during the four longwall operations in the strata beneath the roof (the de-stressing strata, Fig. 1), 156 (2,9%) were high energy events ($\geq 1\times10^5$ J), the total energy output being $1{,}8\times10^8$ J. When two faces in the roof strata (de-stressed strata) were worked (Fig. 2), the total number of registered shocks was lower (3161) yet the parameters of high-energy events were: the number of events 158 (5,0% of the population), energy factor being $2{,}3\times10^8$ J, exceeding the relevant levels registered for the de-stressed zone.

The first galleries driven prior to mining operations were the main entry and subsidiary road. While the road was approaching a nearby fault with the thrust between 50 to 70 m, the first rockburst occurred causing a seismic shock 5×10^4 J with its epicentre located 20 m from the working face.

As the rockburst risk increased when the boundary caving drift 1 J was being driven, the decision was made that the transverse wall ‘0’ should become the opening plot, yet five months after the start of the longwall operation another rockburst occurred generating seismic event with energy 2×10^6 J, its epicentre was 50 m ahead of the face. When longwall operations ‘0’ were completed, the working of the roof strata seam began in the configuration of two longitudinal longwall faces 1 J, 2 J (longwall operation 1 J began first). Nearly two months later, however, the

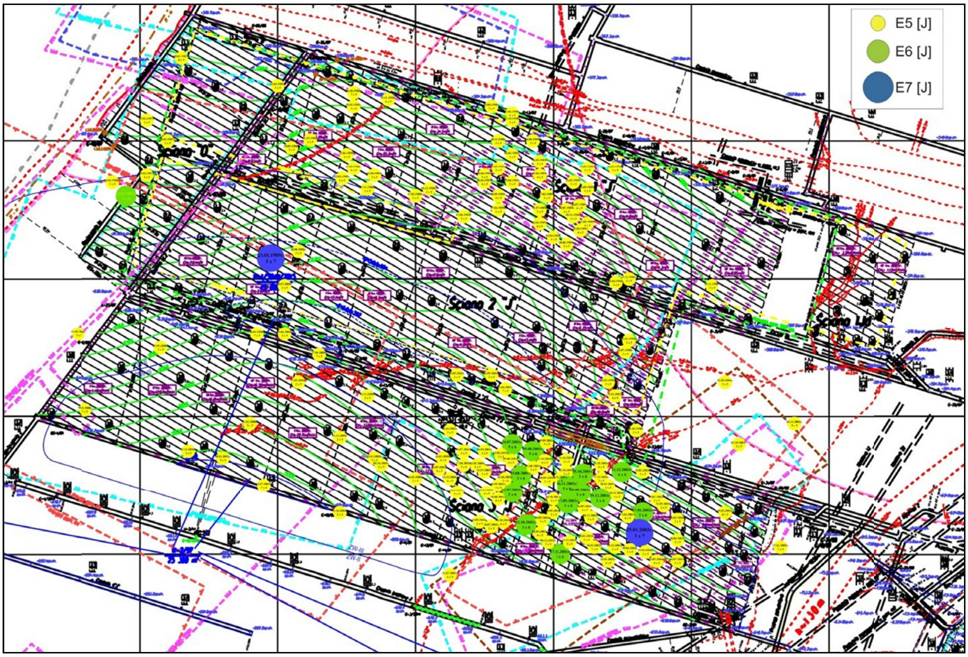

Fig. 1. Location of foci of high-energy seismic events during the mining of the de-stressing strata

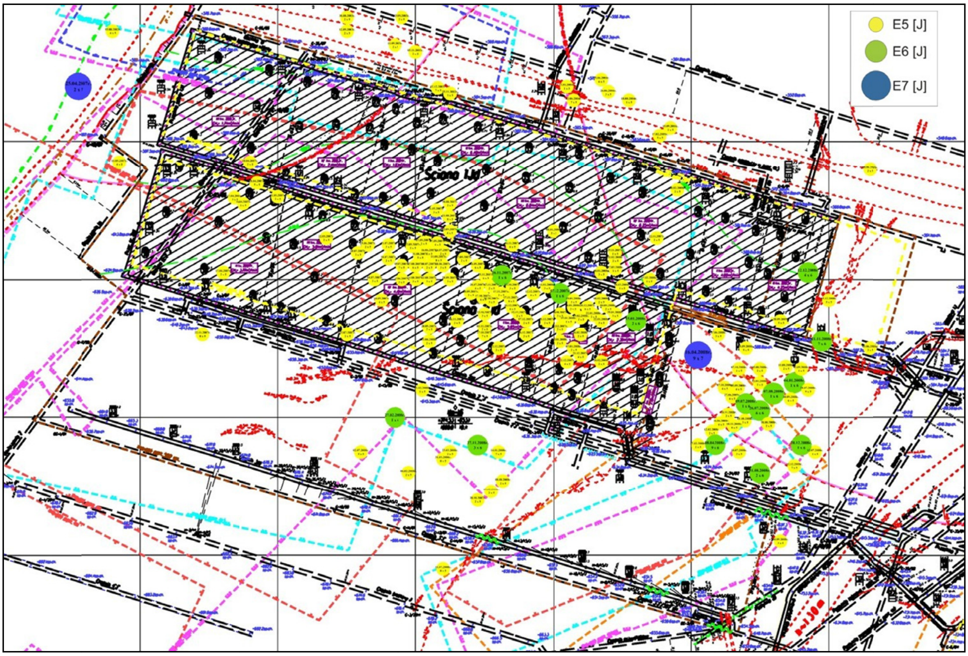

Fig. 2. Locality of epicentres of high-energy events registered during the working of de-stressed strata

third rockburst occurred triggerred by a seismic event of 7×10^5 J, its focus located at a distance of 60 m ahead of the face 1 J and 40 m from the main entry. During the longwall face operation 3 J in the roof strata, the fourth rockburst occurred as a result of a seismic event 3×10^7 J (according to the Central Mining Institute 9×10^7 J), its epicentre was located 150 m on the face range, in the middle section of the panel. Simultaneously, the longwall operation 1Jd continued in the floor strata situated under the caved-in sections of excavation 1 J. The highest seismic activity, manifested by repeated quakes with energy of the order 10^5 J, was registered during the face advancing under the edge of mining operation 1 J (in the roof strata). After completing the operation 3 J, the longwall operation 2 Jd began in the floor strata seam. In the course of mining operations that continued about a year after the longwall started, another rockburst occurred triggered by a seismic event of 9×10^7 J (the highest seismic energy registered so far) producing major damage. It's epicentre was located along the face range, about 180 m from the face and nearly 60 m from the subsidiary road 1 Jd.

3. Conceptual and theoretical backgrounds of the stress state description beneath abandoned workings

With reference to the two aspects involved in mining operations and their impacts on the surrounding shock-prone rock strata and coal seams, a thorough plan of mining activities in the neighbourhood of old abandoned excavations should include a reliable rockburst hazard assessment taking into account two types of interactions. This study investigates the first aspect pertaining to the impacts of old excavations and abandoned workings in another seams (or strata), often encountered by mining practitioners. From the standpoint of geomechanics, this is a 3D problem (mostly due to the complex geometry of worked-out plots), yet the first approximation relies on a 2D solution. In terms of values of rockburst hazard indices, thus obtained estimates will be less favourable and hence provide for extra safety margins. To determine the vertical component of the stress state in the deposit horizon, a modified 2D model of a longwall system is recalled (Fig. 3). This model is based on the cylindrical plate bending theory for a deformable substrate, represented by the mined seam and caving-in or backfilling conditions (Sałustowicz, 1968).

The underlying assumption made at the stage of model development was that rock strata surrounding the face entry should exhibit the equivalent bending rigidity taking into account the floor and main roof parameters. Old excavations were treated as a linearly deformable medium, the coal seam viewed as a nonlinearly deformable medium, its stress-strain characteristics approximated by straight line sections in accordance with the energy equivalence criteria (Zorychta et al., 1986; Mróz & Nawrocki, 1989; Baryakh & Gegin, 1997; Lin'kov, 2001). The equivalent roof deflection was assumed to be induced by the bending moment whilst the working zone interactions were governed by normalised values of the powered support capacity. In consideration of the triaxial stress state in the coal seam and potential damage to its original structure implicated by the Coulomb-Mohr criterion, the actual behaviour of the unworked coal body near the longwall face (i.e. retaining its elastic condition, formation of fracturing or loosening zone) is associated with properties of the rock strata, the level of advancement of longwall operations and technological parameters.

In consideration of the widely manifested impacts of abandoned workings (old excavations) manifested as additional static loads, the model was modified accordingly to incorporate

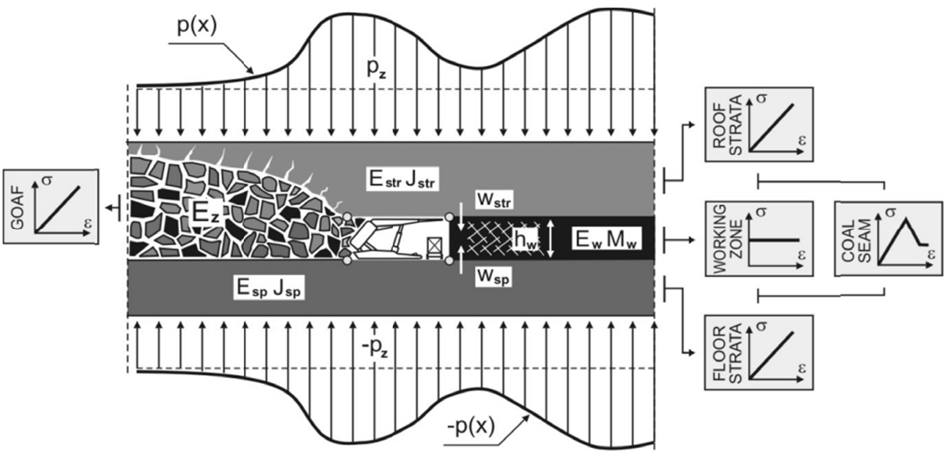

Fig. 3. Geomechanical model of the longwall system

individual (analytical or numerical) functions governing the non-uniform stress distributions (Chlebowski, 2013). In the present study the impacts of abandoned workings both in the overlying and underlying strata are represented by a nonlinear curve (Fig. 4).

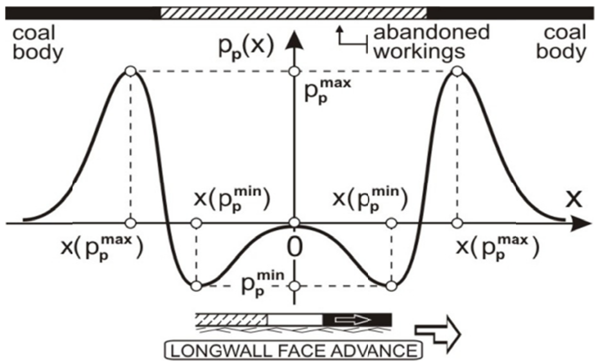

Fig. 4. Schematic diagram of additional stress in the proximity of abandoned workings

Assuming the given finite span of extraction, the external loading diagram indicates, widely speaking, the zones of stress reduction generated by the abandoned workings and the high stress concentration zones associated with interactions of mining edges (at the end of the unworked coal body) as the borderline of two media differing in their stress-strain characteristics. The curve, therefore, expresses the standard distribution of impacts intensity in the function of horizontal distance. It is symmetrical with respect to the axis of the overcutting (underhole) excavations, revealing local extremes associated with the maximum de-stressing on the horizon of overcut (underholed) seam. Therefore, the displacement and stress variations on the face in the entire seam can be monitored during the face advancement in the impact zones affected by the presence of abandoned workings.

4. Scope and results of analytical modelling

The outlined model was employed to solve the rock strata mechanics problem yielding a set of procedures and analytical expressions defining the displacement and stress values in individual components of the system: in old excavations, working zone and in the undisturbed coal seam. Finally, a mathematical simulation model was developed incorporating a dedicated individual computation algorithm. The source code was written in Object Pascal (compiled under Borland Delphi 2006; Borland Software Corporation, 2002), taking into account implementation procedures to handle output formulas and equations from the CAS (computer algebra system) module (Wolfram Mathematica ver. 5.1; Trott, 2006). The model was applied in simulations of the face advance for static positions of the face derived by successive modification of its distance to the axis of the old excavations and in subsequent steps of the calculation procedure, by monitoring the position of a single point on the face. The horizontal range was set in the interval broad enough to capture the starting and final points representing the influence that the loading function has on the value of observed parameters. It is assumed that such a procedure should be an approximation of the mining operation and in consideration of the fact that the potential damage to the seam structure is going to start in the face (where the state of stress is uniaxial), the procedure may be well employed to identify unfavourable rockburst conditions.

As the simulations were performed for the purpose of demonstration only, the averaged values of geomechanical rock parameters were used (Kidybiński, 1982; Bukowska, 2002), alongside typical parameters of the longwall system technology. The initial assumption was that the mining operations are well developed in terms of an adequate span of excavations, the worked seam was 3 m thick and the roof management involved the backfilling of worked out voids (governed by the modulus of elasticity of the excavations), whilst width and capacity of the powered support was selected as the average of typical powered support sets operated in these collieries. The ratio of post-failure modulus to longitudinal modulus of elasticity is taken to be unity (1,0), for specified (instantaneous and residual) resistance parameters of the seam in relation to gravity-induced vertical stress. Assuming the direction of face advance coincides with the abscissa in the Cartesian coordinate system, the calculations were performed for the old excavations separated by two sections of unworked coal body whose impacts are defined in the schematic diagram of external loads (Fig. 4) with the following features:

- the function has four global extremes (two minima and two maxima) and one local maximum (zero) in the axis of symmetry,
- horizontal co-ordinates of extreme points $x(p_p^{\min})$, $x(p_p^{\max})$ are ±25 m (minimum) and ±50 m (maximum),
- the total range of impact zone is ±90 m.

For comparison, two variability ranges of extreme values were considered, assuming the identical shape and geometry of the approximating function, including the localities of horizontal co-ordinates of the extreme:

- in the first case (model A) the maximal stress loading value ($p_p^{\max}$) was equal in magnitude to the absolute value of the initial gravity-induced load whilst the minimal stress relief ($p_p^{\min}$) – was equal to half its value,
- in the second case (model B) the maximal stress loading was equal to 40% of the initial gravity-induced loads, the minimal value was 20%.

Underlying the model curves was the principle that the decrease of the maximum impacts (stress concentrations) generated should coincide with the decrease of the absolute stress relief value. This approach was adopted because of the need to account for the age of excavations (difference in time between the de-stressing and de-stressed working) and their vertical distance from the investigated seam. Simulation results are collated in the form of 2D plots showing the distributions of the following parameters:

– displacement (convergence) of the immediate roof (Fig. 5),
– vertical stress concentration factor, defined as the ratio of the current value of secondary stress to lithostatic stress due to depth (Fig. 6).

Their variability on the longwall face is analysed as the function of a current coordinate defining the distance from the face to the vertical axis in the old excavation. In consideration of the estimated extent of impacts of rockburst events on the state of stress and strain in the worked seam, the calculation procedure was restricted to the interval from –100 m to +140 m (in relation to the middle section of overcutting/ underholing operation). In terms of mining practice, it means that the initial (around 65 m) and final (105 m) section of the face range corresponds to the face locations beneath or over unworked strata, that is in the zone where the de-stressing effects are absent. The remaining part (around 70 m) corresponds to the face position beneath the old excavations, i.e. in the de-stressed zone.

When evaluating the results, it is worthwhile to mention that for the given approximating function the modeled operations will involve the face passage through two extreme stress loading zones (with external maximum associated with additional stress, Fig. 4) and through two de-stressed zones (featuring the stress minimum and the local maximum in the middle part of the old excavation). This pattern is illustrated by the geometry of vertical displacement (roof convergence) distribution in Fig. 5, revealing two zones of increased convergence and one zone where convergence is lower than in the undisturbed conditions. It appears that the impact (the model's response to the applied loading) is shifted and its extent greater as the mining operations advance. Of particular importance is the fact that the maximum roof subsidence registered when approaching the boundary between old excavations and undisturbed strata is higher for the nar-

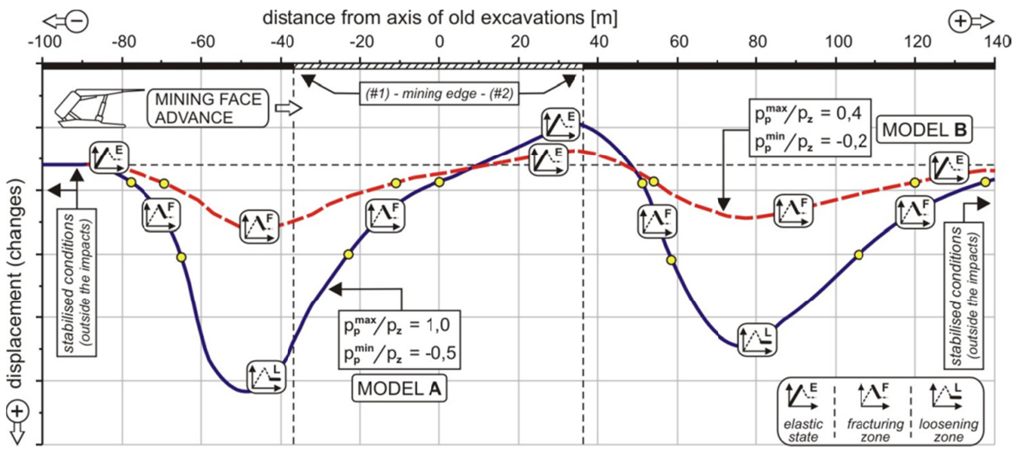

Fig. 5. Vertical displacement (roof convergence) distribution on the longwall face

rower horizontal range, and becomes lower when passing through the other edge line between the old excavations and undisturbed strata, though the range of horizontal impacts is greater. In terms of geomechanics, this implies more difficult mining conditions during the mining face advance from undisturbed strata towards the old excavations while compared to the face advancing from the old excavations towards the undisturbed strata. It is worthwhile to mention that gradients of vertical displacements associated with the face passing these two boundaries differ in the sloping on the descending end and the actual increase of the relevant parameter (displacement) in relation to the extreme value.

In consideration of the adopted loading pattern, the lowest roof convergence in the face zone corresponds to the face position beneath the old excavations, yet the plot of convergence is strongly asymmetric, featuring a minimum shifted by about 30 m towards the other undisturbed strata section (in relation to the axis of old excavations) and located underneath its edge. Unlike the external stress loading, the convergence plot does not reveal a double minimum.

Thus, the amount of vertical stress distribution (Fig. 6) is linked to the registered variability of the displacement state. The highest stress variability in the context of potential triggering of stress-related phenomena on the face is associated with the highest stress-loading zones and further face advance (defined as the face range positions in relation to the abandoned workings) consists of the following stages:

- model A:
  - undisturbed structure of the unworked face sections, first interactions and stress increase up to the critical stress loading levels (face range section 15 m in length),
  - a fracturing zone emerging on the face, stresses decrease in accordance with the full stress characteristics of the medium (face range section about 10 m in length),
  - loosening of the face (face range section about 40 m in length),
  - mining face position again in the fracturing zone and associated stress increase in terms of unixial compressive strength (face range section about 25 m in length),
  - the undistrubed rock strata in the elastic state, initial stress decrease followed by increase up to the critical value (face range section about 50 m in length),
  - another fracturing zone on the face, decreasing stress values (face range section about 10 m in length),
  - loosening of the face zone (face range section about 45 m in length),
  - mining face position again in the fracturing zone and associated stress increase in terms of unixial compressive strength (face range section about 30 m in length),
  - return to the stabilised elastic phase conditions.
- model B:
  - initial point of impacts (undisturbed structure of the face) and stress increase up to the critical stress value (face range section about 20 m in length),
  - the fracturing zone emerges on the face, stress reduction followed by stress increase towards the unixial compression strength (face range section about 60 m in length),
  - the undisturbed coal body in the elastic state, an analogous stress distribution as in the previous case, revealing a local minimum (face range section about 65 m in length),
  - another fracturing zone (face range section about 65 m in length),
  - return to the stabilised elastic phase conditions.

With reference to the stress characteristics during the mining face advance, it appears that in qualitative terms the superposition of impacts produced by two mining edges (undisturbed

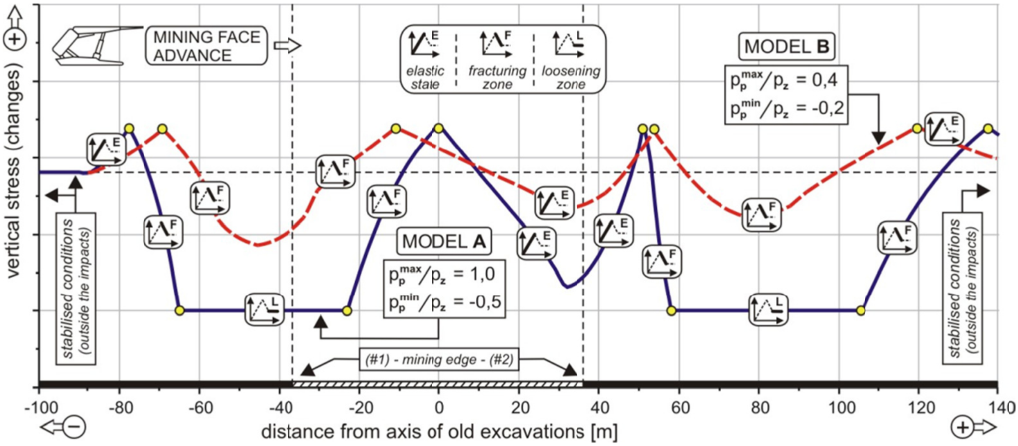

Fig. 6. Stress distribution on the longwall working face

strata – old excavations, old excavations – undisturbed strata) is captured well. In quantitative terms, there are significant changes in the stress values. In both cases the maximum of the stress loading function (models A and B) coincides with the formation of structural damage zones. For p_p^{max}/p_z = 1,0 (model A) there is also a seam loosening zone, i.e. the failure condition in which the structure of the medium is crushed, the only forces holding the particles together being the friction forces. Due to the registered minimum displacements under the sections of abandoned workings, the medium maintains its elastic properties, like in the case of areas free from additional stress loading. Defined by the parameters p_p^{max}/p_z (p_p^{min}/p_z) the extreme values of the function governing the behaviour of old excavations are major determinants of the critical strength of the investigated seam (Table 2) and the extent of failure zones; besides are manifested via delayed occurrence of effects registered in the undisturbed strata.

TABLE 2

Stress zones in the mined seam in subsequent stages of mining operations

Model	Face position with respect to the abandoned workings	Characteristics of the seam structure at the face		
		Elastic state	Fracturing zone	Loosening zone
A	outside the impacts	+	–	–
	beneath/over the undisturbed strata (#1)	+	+	+
	beneath/over the old excavations	+	+	+
	beneath/over the undisturbed strata (#2)	+	+	+
B	outside the impacts	+	–	–
	beneath/over the undisturbed strata (#1)	+	+	–
	beneath/over the old excavations	+	+	–
	beneath/over the undisturbed strata (#2)	+	+	–

(#1) face range section ahead of the edge between undisturbed strata and old excavations
(#2) face range section beyond the edge between old excavations and undisturbed strata

The identified critical stress regions (located in the undisturbed strata along the face range sections in the de-stressed zone) are mostly associated with the approaching edge between the undisturbed strata and old excavations. Hence, when evaluating modelled conditions, it is reasonable to expect enhanced rockburst hazards at this stage of mining operations. Simulation results confirm that despite the occurrence of the stress relief effect, rockburst events beneath or above the abandoned workings cannot be precluded. The rockburst risk is determined by local geological and mining conditions, in the first place by the type and span of old excavations, their age and the vertical distance from the currently worked seam.

5. Conclusions

This study presents the results of modelled cases related to the stress and displacement state in the longwall face mining areas affected by the presence of abandoned workings that is a typical problem confronting mining practitioners. Theoretical considerations and analyses lead to certain conclusions, yet due to the fact that simulation results have relevance to selected situations only within the course of mining operations (face advancing beneath and over old excavations) and are based on averaged values of geomechanical parameters of the rock strata, they should be considered in qualitative terms only.

- Regardless of their type and origins, mining coal remnants produce non-uniform stress distributions in the rock strata in relation to the lithostatic stress values. The extent and intensity of stress variations directly impact on the state of displacement and stress on the face worked in the impact zones. As a consequence, the rockburst hazard levels will vary.
- Old excavations prompt the formation of de-stressed zones where the vertical stress values are lower. Basically, in de-stressed zones the likelihood of a high -stress event is lower, hence the rockburst risk levels on the face range will be reduced.
- The actual pattern and locations of extreme values in plots of displacements and stress registered on the working face do not coincide with analogous patterns in model loading functions. Characteristic points on the curve representing the rock strata response are shifted with respect to relevant points on the external load plot, which captures the impacts of old excavations. As a consequence, locations where the rockburst hazard levels are the highest need not be the points of maximal loading.
- Mining operations in the areas affected by the presence of old excavations involve the face passing two edges: undisturbed strata – old excavations, old excavations – undisturbed strata. In the context of variability of geomechanical parameters governing the behavior of the face zone, the least favourable conditions prevail in the first case. Hence, working the face towards the old excavations in the overlying (underlying) strata gives rise to higher rockburst risk.
- Despite the sustaining de-stressing effect on selected face range sections, the critical stress zones can occur in the face region. Therefore, a rockburst occurrence underneath or over abandoned workings cannot be precluded.
- With the passage of time between the de-stressing and de-stressed operations and with increasing vertical distance between the de-stressing and de-stressed seams, the rockburst risk tends to decrease. Simulation results for the loading patterns in model B confirm the lower (in relation to model A) intensity of high-stress events along the working face.

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