prof. dr hab.inż. Jan Butra [1)]
dr hab. inż. Jan Kudełko [1)]

Rockburst hazard evaluation and prevention methods in Polish copper mines

Keywords: rockburst, geological hazards, copper mining, risk assessment, prevention

Abstract
Longstanding mining of copper deposit in the Legnica-Glogow Mining Basin (LGOM area) enabled to gain broad experience concerning the impact of geological and mining conditions on seismic and rockburst hazard. Basing on gathered data, the methods of rockburst prevention for deep copper mines were developed. Methods of rockburst hazard evaluation as well as rockburst control methods constitute a set of rockburst prevention. The prevention methods due to their nature and location within the production process can be the passive and the active ones. Active methods of rockburst prevention consist in liquidation of stresses in the areas of their concentration through controlled generation of rock-mass tremors and rockburst by blasting works (group winning blasting, release blasting in rock-mass and in pillars able to accumulate the stress as well as in the roof and floor). Whereas the group blasting works as a basic method are very effective in the copper mines conditions. Provocation of dynamic events makes possible the control of time of their occurrence. In Polish copper mines all blasting works are made during the absence of miners in the mining fields. Daily distribution of both the number of recorded strong seismic events and the volume of energy released confirm the advisability of using this kind of rockburst hazard prevention. The rockburst hazard prevention methods developed during the 40 years of copper deposit extraction are economically reasonable and offer the sufficient effectiveness under the high rockburst hazard conditions.

Introduction

The bed shaped copper deposit on the Foresudetic Monocline (SW Poland) occurs on the big depth (from 600 to 1,400 m), has small inclination (about 4°), variable thickness (from 0.4 to ca. 20 m) and changing lithological profile (sandstones, dolomites and shales). Over its roof occurs the suite of dolomites and anhydrites having the strengths ten times higher than of the sandstones lying under the deposits bottom.

[1)] *KGHM CUPRUM sp. z o.o. – CBR, ul. gen. Wł. Sikorskiego 2-8, 53-659 Wrocław*

Deposit and the surrounding rock have natural capability to accumulate the elastic energy and inclination to its violent release. The substantial impact on the formation of dynamic seismic events has also mining factors, which are mining and roof control methods, high concentration of mining operations and impact of already mined out areas.

The deposit extraction using room-and-pillar methods started in 1967. At present 32 million tons a year are mined in three big underground mines – "Lubin", "Polkowice-Sieroszowice" and "Rudna". The first strong rock-mass tremor, having the magnitude of 2.8 took place on 31 July 1972. With the progress of mining, the regular increase of number and size of tremors has been observed and some of them have been the cause of rockbursts.

The analyses of the seismic activity level in copper mines with regard to the number of rock-mass tremors recorded in the years 1990-2010 show that this value was systematically growing up, reaching the highest value since the beginning of mining operation in 2000.

Percentage of $\geq 10^8$J energy tremors within total number of rock-mass tremors during this period is on the level of 0.20%, while the share of those tremors energy within the total emission of seismic energy reaches almost a half of the entire value. The rest part is a sum of other tremors energy.

Taking into consideration energy of mine rock-mass tremors and their impact on workings stability loss, it can be said that, the crucial influence on the tremors hazard in the Polish copper mines have high energy tremors, which measured seismic energy value is higher than 10^5J. During last 21 years (1990–2010) in KGHM Polska Miedz S.A. the total of 11 200 such tremors were recorded, and their cumulative energy (amount of measured seismic energy) was 70,48 GJ. This means that along the annual output of 32 million tons of copper ore, over 534 high energy rock-mass tremors, having total energy of 3,3 GJ, occurs. The number of events bearing the consequences shows the real hazard caused by tremors induced by mining operations (323 events from 1990 to 2010).

Table 1

Seismic activity parameters in copper mines in years 1990–2008

Year	Number of tremors in energy classes [J]									Sum of energy [×10⁹J]
	10^3	10^4	10^5	10^6	10^7	10^8	10^9	Total	S	
1990	676	454	294	130	23	-	-	1 577	4	1,291
1991	575	359	230	104	26	-	-	1 294	5	0,920
1992	678	504	341	135	23	-	-	1 681	16	1,222
1993	692	641	300	153	39	4	-	1 829	20	3,053
1994	724	583	279	121	33	7	-	1 747	15	2,841
1995	754	621	308	134	29	3	-	1 849	19	1,866
1996	870	741	425	183	36	1	-	2 256	17	1,823
1997	795	749	361	144	60	3	-	2 112	21	2,767
1998	637	581	293	107	42	4	-	1 664	13	2,799
1999	869	669	267	98	40	10	-	1 953	9	3,957
2000	1 040	737	324	141	43	4	2	2 291	13	7,124
2001	1 501	1 062	499	167	53	9	1	3 292	14	6,270
2002	1 444	1 030	516	116	44	17	1	3 168	19	7,390
2003	1 336	981	411	117	37	5	-	2 887	18	3,430
2004	1 411	890	422	137	52	9	1	2 922	19	6,088
2005	2 185	1 492	584	157	36	9	-	4 463	14	4,088
2006	2 433	1 529	648	169	46	8	1	4 834	17	5,718
2007	2 988	1 372	584	156	35	2	-	5 137	15	2,047
2008	2 663	1 333	465	116	22	1	-	4 600	16	1,278
2009	2 132	1 026	402	126	45	1	-	3732	17	1,872
2010	2 193	1 178	421	115	41	4	-	3952	22	2,641

S – number of tremors with consequences

1. Types of rockbursts and factors determining their occurrence

Rockbursts occur mainly in underground mines workings. They are also observed during excavation of tunnels and adits. Strong rockbursts cause casualties and serious material losses (destruction of workings as well as machines and equipment located there).

In Poland the rockbursts occurred firstly in hard coal mines. Studying those events, three types of rockbursts were identified: bed, roof and floor. It was mainly a conventional subdivision. The most frequently the stroke causes crushing and collapse of rocks together with throwing them into the working as well as floor response in the form of sudden elevation. In such situations rating of the rockburst into the given type is very difficult. Defining the types of rockbursts the following principle is used: qualification of the rockburst into the certain group decides the location of tremor, causing the rockburst, center. Thus the bed rockburst is caused by tremor having its center within the bed, roof rockburst by tremor with its center in roof rocks while floor rockburst by tremor located in the floor.

Generally mine rockbursts, shortly further called „rockbursts”, may be divided into stress, stroke and stroke-stress ones. Mine, tectonic rockbursts are also identified [3] (fig. 1).

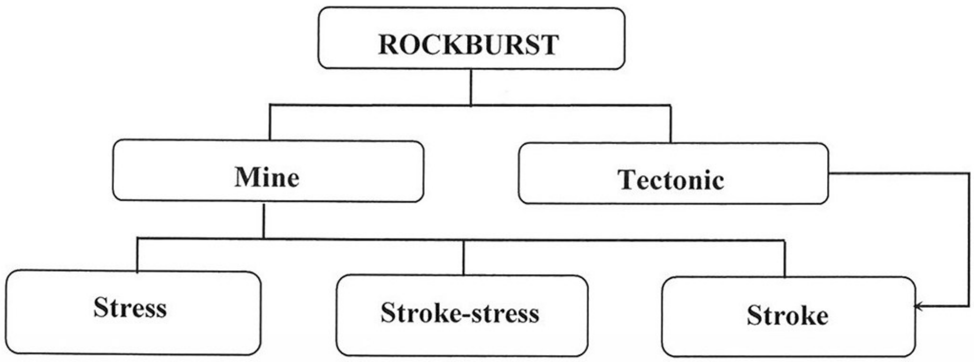


Fig. 1. Types of rockbursts

Rockbursts occur as a result of currently carried out or completed mining activity. Tectonic rockbursts are related with tectonic zones. Stress rockbursts are the result of slow, quasi-static increase of stresses inside the bed, in the vicinity of workings, and then sudden release of gathered energy. Level of stress rockburst hazard may be defined basing on the results of measurements made inside the bed.

Stroke rockbursts are the result of sudden application of force following the break of thick monolithic rock layer in the bottom or top of deposit, and its relocation. Level of stroke rockbursts hazard may be evaluated using the results of investigations carried out in the rock surrounding the deposit as well as predictions with regard of place and conditions of surrounding rocks breakage (cracking). Tectonic rockbursts are, to some extent, similar to stroke ones.

Such interpretation of stress and stroke rockbursts refers to extreme cases, but between them there is a wide range of stroke-stress events, when at high values of stress condition constituents, even relatively slight impulse of stroke, coming from the rock-mass surrounding the layer, can result in the rockburst.

Longstanding observations and studies carried out in copper mines, showed that the impact on seismic hazard have geological and mining conditions as well as organizational issues. The following factors are classified as geological ones having impact on the seismic hazard:

- depth of mining and related with it primary pressure of the rock-mass,
- lithology of rock-mass,
- thickness of deposit being mined,
- tectonics and presence of discontinuity planes,
- occurrence over the deposit top rock layers of high strength and great thickness,
- geomechanical characteristics of rock-mass,
- rocks tendency to generate the mine tremors.

Among the natural causes the most important is high primary pressure of rock-mass, resulting from both big depths of mining and residual pressures being the effect of tectonic disturbances of the deposit, thick-layer structure of the rock-mass and natural tendency of rocks to the rockbursts. The first type of pressures is uniquely a result of the mining depth. Residual pressures are often difficult to find out, as well as hard to evaluate. Additionally, close to some tectonic disturbances, the presence of lateral pressures of substantial values, is discovered, in the neighborhood of the ones the rock-mass can be released [3]. From the experience of Polish hard coal and copper mining appears that higher rockburst hazards, at comparable depth of mining operations, is in case of deposit occurrence within the rocks having greater strength, especially when over the deposit top, strong and thick rock layers occur. About the potential hazard decide some rock properties such as big strength and elasticity. It does not mean that rock having low strength and elasticity cannot cause the rockburst. In such case, however, value of stress condition constituents must be much higher than for the rocks with great strength and elasticity. The crucial role plays also a velocity of load growth. In Polish underground mines, the increase of rock-mass seismic activity while mining the thick deposit is

noticed. This relationship can be related with bigger deformations of rocks and greater possibility of unstable zones occurrence in the rock-mass.
Excavating the mine working disturb the balance within the rock-mass. During stabilization of new balance, the potential energy is released from the rock-mass, part of which is turns into the seismic energy. Rocks inclination towards accumulation of elastic deformation energy and its sudden emission is a genetic feature. However, the volume and rate of energy release and, to some extend, rock strength, depend on the mining technology used. The experience indicates the factors generating seismic and rockburst hazard are:

- mining method,
- roof control method,
- pattern of deposit cut,
- concentration of mining operations,
- spatial limits of mining operations.

Among technical sources of rockbursts, the most critical is local concentration of stresses caused by mining activity. It may be generated by improperly selected mining methods and wrong mining pattern or strong roof rocks over the mined out area. It appears from mining practice, that also an excessive concentration of mining works decide about the considerable increase of rockburst hazard. This problem should be analysed under the function of time necessary for rock-mass relaxation and through the issue of competent coordination of mining operations. The important factor increasing the hazard level is spatial restriction of mining works (rests, support pillars, workings located in front of face).
Essential impact on rockburst hazard also have organizational factors:

- underinvestment of mine,
- defective mine works,
- defective prevention works.

Organizational factors concern the insufficient mine fitting with equipment and measuring installations as well as deficiency in mine personnel training. This may result in errors during mining operations and implementation of rockburst prevention.

2. Rockburst prevention and its range

Widely interpreted rockburst prevention includes methods of rockbursts hazard level evaluation as well as rockburst control methods. The problem of rockburst hazard control refers to almost whole production process, from planning of mining works to drifts excavation and deposit mining. Generally the prevention means technical, engineering and organizational measures aimed to prevent, limit or eliminate the existing hazard. Correctly planned rockbursts prevention should include the following stages:

– evaluation of hazard causes and sources,
– selection of hazard control methods,
– implementation of accepted prevention methods,
– verification of prevention effectiveness.

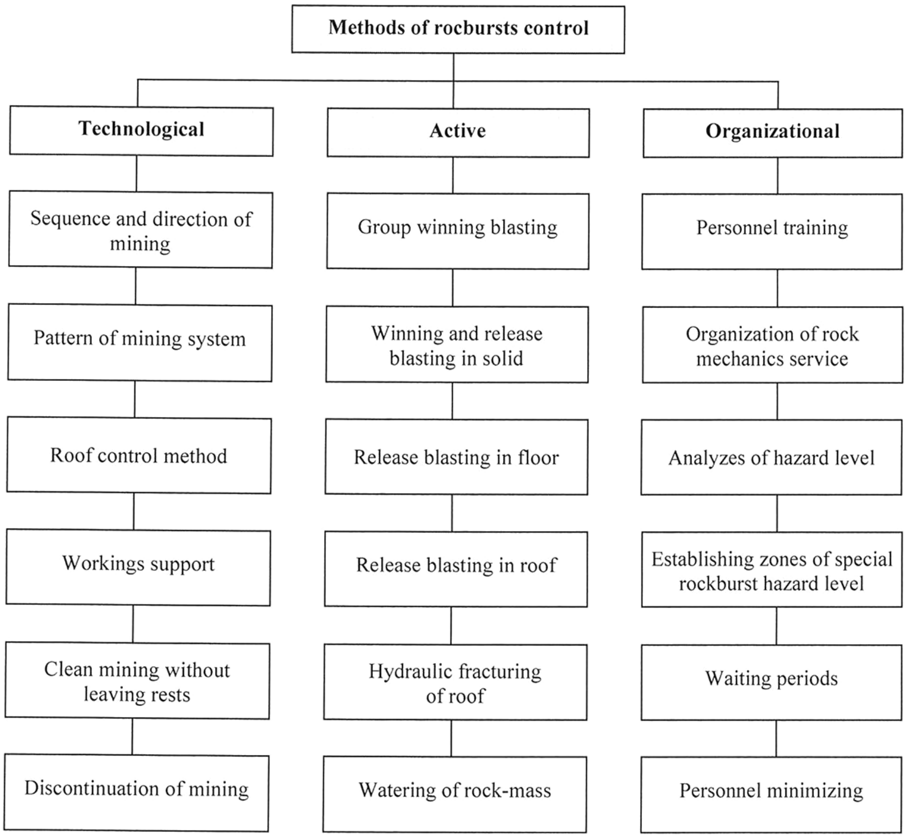


Fig. 2. Methods of rockburst prevention

Selection of rockburst prevention methods depends on the advance of mining operations and level of hazard sources i.e. simultaneous presence, under certain geological and mining conditions, the factors determining the type and level of rockburst hazard. Properly selected and correctly applied prevention should be fitted to the scale of known rockburst hazard and effective, what means:
– elimination of hazard or limitation of its level,
– minimizing the rockburst effects.

Effective rockbursts prevention should be based on extraction design adjusted to the hazard level and on suitably selected mining technology as well as short-term (active) actions with monitoring of hazard level changes.
Rockburst prevention methods are divided with regard of their essence and possibilities of their application during the production process (fig. 3).

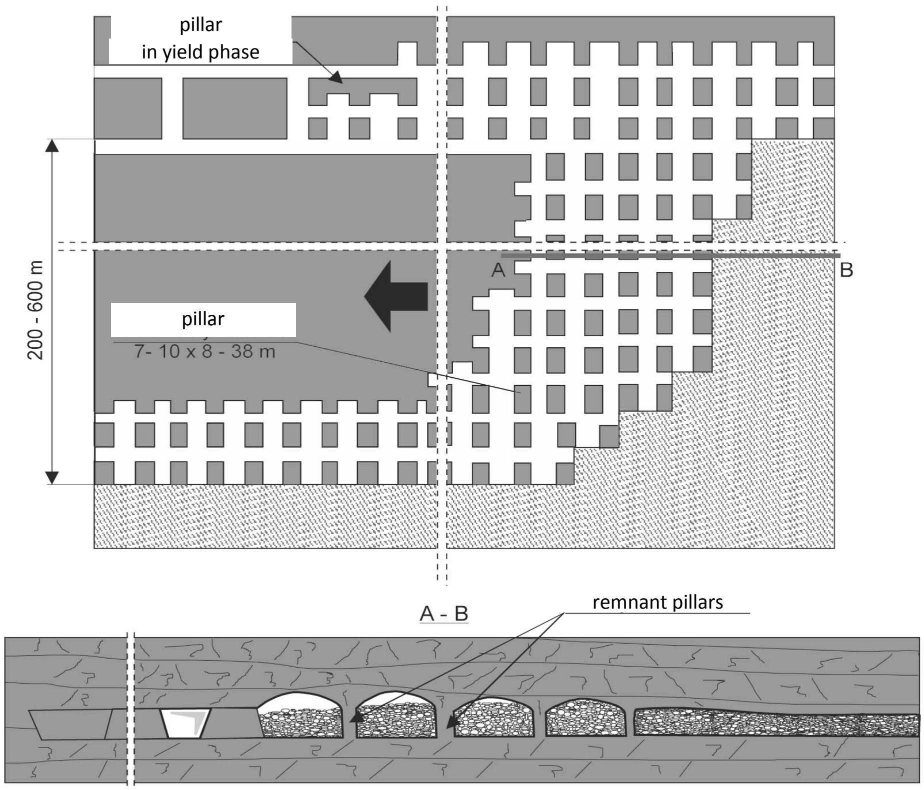


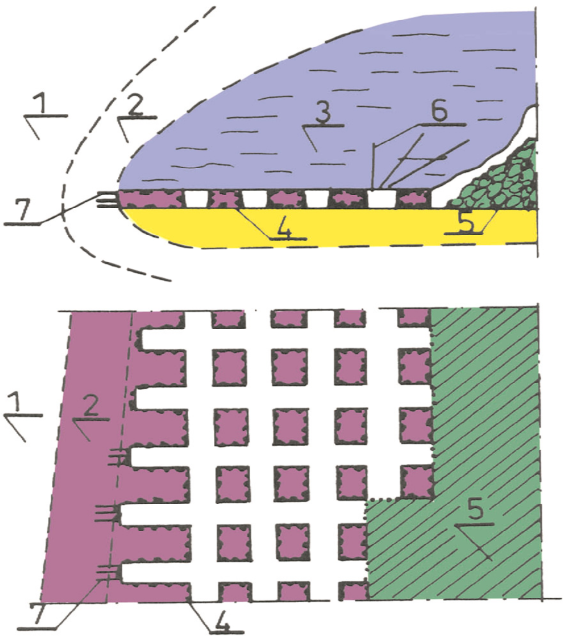
Fig. 3. One-phase room-and-pillar method with roof deflection

3. Rockburst prevention in copper mines

Copper deposit mining is carried out using one-stage room-and pillar methods with gobs liquidation by roof deflection on remnant pillars (fig. 4) or filling them by sand backfill. Their specifics is, that the technological pillars, separated by rooms and so called “strips”, already along the line of cut, pass into post-failure conditions as a result of mining pressure. Being at this stage they reach high yield and work in the mining field with post-failure remnant resistance. In order to correctly control the stiff roof using room-and-pillar mining methods, its stability at every stage of ore winning is of great importance. The stability is determined mainly by the area of separated technological and remnant pillars as well as their slimness and post-failure strength of rocks present in the excavation profile. Those parameters are selected separately depending on parameters of mining field. Forty years long experience of copper deposit mining under rockbursts hazard allowed to develop several passive (technological) rules, which are aimed to minimize or eliminate tremors consequences. Among other things they consist in:

- maintaining even line of cut and keeping in parallel the line of cut and liquidation,
- keeping the appropriate distance between line of cut and line of liquidation of technological pillars,
- applying the so called „deep yield" of solid and increasing the number of faces by locating the technological pillars perpendicularly to the edge of the solid being cut,
- selecting the pattern of technological pillars cut to ensure their operation under the post-failure strength phase,
- maintaining the correct course of front line, direction and progress, suitably to the present geological and mining conditions (towards: the gobs line of next field, the workings passed by front, the fault planes etc.),
- avoiding the large pillars and solids in the zones adjacent to not-yield gobs,
- elimination of driving the galleries ahead of front,
- deconcentration of mining operations by keeping the relatively big distance between active fronts and slowing the mining rate through doing the group blasting of faces only once or twice a week,
- regulation of pillars slimness through enlarging up to 10 meters the workings width at the roof, when sandstone with anhydrite binder is present in the faces,
- determining the special zones of rockburst hazard, in which the number of working miners is reduced to a maximum,
- introducing the waiting times after blasting adequate to the mining conditions.

Respecting these rules in currently mined regions brings the expected results i.e. substantial reduction of dynamic events of stress origin.
Apart from technological methods the rockburst hazard reduction in copper mines is carried out also by using the active means. They are aimed to force the emission of energy accumulated in the rock-mass by relevant blasting works. The provocation of seismic events, also the ones connected with rockbursts of stress releases, is obtained by removing the roof support and additionally by over loading the solid zone by blasting the charges in faces simultaneously along the extensive section of front (fig. 5).



1 – not mined rock-mass, 2 – zone of mining pressure effect,
3 – released and delaminated rock-mass, 4 – bed (pillar) solid under post-critical state,
5 – cave-in forced by blasting, 6 – caving blasting holes, 7 – face blasting holes.

Fig. 4. Method of provoking strong seismic tremors and rockbursts in room-and-pillar mining systems in LGOM mines

In order to intensify the provocation effect of winning blasting, the long release&cut holes having bigger diameter are used in faces. This method gives the overcharge of faces with explosives and enlarging the slices.

Active methods consist in provoking the rock-mass tremors by:

- tremor and winning blasting of mining faces (with maximum number of blasted faces),
- release blasting in solid, by blasting-off the explosives in additional holes of enlarged length and diameter, made both apart of and together with blasting the faces,
- release blasting in pillars able to cumulate the stresses,
- making the release blasting in floor.

The first three active methods are obligatory in mining fields with high rockburst hazard. Practical measure of effectiveness of provoking result of blasting works is share of tremors which occurred while waiting after blasting, in their total number and respective percentage share of released seismic energy.

Basing on longstanding experience gained during extraction under rockburst hazard conditions as well as analyse of seismic tremors occurrence time distribution, the minimal period of waiting after technical blasting works was determined (tab. 2). Absence of workers in the mine working during that period, limits the possibility of accidents, caused by seismic tremor consequences, with involvement of people.

Table 2

Minimal periods of waiting after technological blasting depending on hazard level

Level of rockburst hazard				
I	**II**		**III**	
	Outside the special zone of rockburst hazard	Inside the special zone of rockburst hazard	Outside the special zone of rockburst hazard	Inside the special zone of rockburst hazard
0.5 hour	1.0 hour	1.5 hour	1.5 hour	2 hours

Effectiveness of provoking the seismic energy emission in the form of high energy rock-mass tremors in years 2003-2010 is presented in table 3. Efficiency of tremors provocation is different in each year, what mainly results form rock-mass properties as well as conditions under which the mining works are carried out.

Table 3

Effectiveness of provoking the seismic energy emission in years 2003–2010 (tremors energy $\geq 10^6$J)

Mine	**Year**	**Tremors energy [$\times 10^6$J]**		
		Spontaneous tremors	**Provoked tremors**	**Total**
„Lubin”	2003	219,6	50,6	270,2
		81,30%	18,70%	
	2004	73,80	99,50	173,3
		42,59%	57,41%	
	2005	177,0	152,0	329,0
		53.80%	46,20%	
	2006	327,0	334,0	661,0
		49,47%	50,53%	
	2007	63,6	83,7	147,3
		43,18%	56,82%	
	2008	52,5	80,5	133,0
		39,47%	60,535	

Table 3 cont.

	2009	9,70	73,40	83,1
		11,67%	88,33%	
	2010	238,0	198,0	436,0
		54,59%	45,41%	
„Polkowice-Sieroszowice”	2003	361,4	670,4	1031,8
		35,00%	65,00%	
	2004	148.40	168.20	316.6
		46.87%	53.13%	
	2005	839,0	754,0	1593,0
		52,67%	47,33%	
	2006	499,0	1080,0	1579,0
		31,60%	68,40%	
	2007	115,3	422,0	537,3
		21,46%	78,54%	
	2008	168,5	112,9	281,4
		59,88%	40,12%	
	2009	154,7	197,6	352,3
		43,91%	56,09%	
	2010	135,0	813,0	948,0
		14,24%	85,76%	
„Rudna”	2003	1066,8	875,7	1942,5
		54,90%	45,10%	
	2004	1020,3	4391,0	5411,3
		18,85%	81,15%	
	2005	1130,0	774,0	1904,0
		59,47%	40,74%	
	2006	941,0	2250,0	3191,0
		29,49%	70,51%	
	2007	465,3	648,0	1113,3
		41,79%	58,21%	

Table 3 cont.

	2008	322,7	341,7	664,4
		48,57%	51,43	
	2009	602,4	652,6	1255,0
		48,0%	52,0%	
	2010	745,0	332,0	1077,0
		69,17%	30,83%	
Total	2003	1647,8	1596,7	3244,5
		50,80%	49,20%	
	2004	1242,5	4658,7	5901,2
		21,06%	78,94%	
	2005	2146,0	1680,0	3826,0
		56,09%	43,91%	
	2006	1767,0	3664,0	5431,0
		32,54%	67,46%	
	2007	644,2	1153,7	1797,9
		35,83%	64,17%	
	2008	54,37	535,1	1078,8
		50,40	49,60	
	2009	766,8	923,6	1690,4
		45,36%	54,64%	
	2010	1118,0	1343,0	2461,0
		45,43%	54,57%	

Between 1990 and 2010 the high energy tremors caused 323 events (rockbursts and stress releases) with consequences in mine workings. It is about 2,1% of total tremors number. Effectiveness of rockbursts and stress releases provocation is shown in table 4.

Table 4

Total and provoked events (rockbursts and stress releases) in copper mines in years 1990–2008

Year	Number of rockbursts and stress releases		
	Total	**Provoked**	**Provoked (%)**
1990	4	0	0
1991	5	2	40
1992	16	13	81
1993	20	13	65
1994	15	11	73
1995	19	14	74
1996	17	10	59
1997	21	18	86
1998	13	9	69
1999	9	5	55
2000	13	5	38
2001	14	8	57
2002	19	9	47
2003	18	7	39
2004	19	9	47
2005	14	6	43
2006	17	8	47
2007	15	8	53
2008	16	8	50
2009	17	6	35
2010	22	11	50

Data in this table attest also that the achieved effectiveness of provoking the tremors with consequences as well as tremors, is mainly determined by rock-mass characteristics in region where mining is carried out and level of local stress. Better or worse effectiveness of dynamic events provocation while using the same methods, is largely a result of high variability of deposit properties.

Conclusions

- Rockbursts prevention in copper mines, both with regard of the development of hazard level evaluation methods as well as of technological and active methods of its reduction is based on present status of mining sciences and level of the respective engineering development.
- It may be stated, that rockburst hazard will be encountered also in the future, and even may increase due to mining on the bigger depth and winning the supporting pillars and deposit rests.
- Despite of great achievements and original solutions with regard of rockburst prevention, the intensification of efforts aimed on this problem, is necessary.

References

[1] Butra J. and Pytel W., 1998, Copper ore exploitation in bump hazard conditions, Mine Planning and Equipment Selection 1998, Singhal(ed), Balkema, Rotterdam, pp. 237-242.
[2] Butra J. and Cieszkowski H., 2000, Experience in exploitation using room and pillar with roof deflection mining systems, International Mining Forum, Publ. Inst. GSM&E Pol. Acad. Sc.Krakow, pp. 7-15.
[3] Dubiński J. and Konopko W., 2000, Bumps, Publ. GIG Katowice.
[4] Pytel W. and Butra J., 2007, 3D FEA Application for Excavation Geometry Selection in Complex Underground Mining Conditions of Polish Copper Mines, Proceedings of the SLGS's 1st Int. Conf. on Soil & Rock Engineering, Colombo Sri Lanka, August 5-11.
[5] Butra J. and Pytel W., 2008, Mining of a deposit under rock bump hazard in a light of numerical modelling, Rudy i Metale Nieżelazne, R-53, No.2, pp. 85-95.

Ocena zagrożenia tąpaniami i profilaktyka tąpaniowa w polskich kopalniach miedzi

słowa kluczowe: *tąpania, zagrożenie geologiczne, górnictwo miedzi, ocena ryzyka, profilaktyka tąpaniowa*

Długotrwała eksploatacja złoża miedzi na obszarze LGOM pozwoliła na uzyskanie znaczącego doświadczenia odnośnie wpływów warunków geologiczno-górniczych na zagrożenie sejsmicznie i tąpaniowe. W oparciu o zgromadzone dane, opracowane zostały metody zapobiegania tąpaniom dla podziemnych kopalń miedzi. Metody oceny zagrożenia tąpaniami, jak również metody kontroli tąpań stanowią system zapobiegania tąpaniom. Metody zapobiegania tąpaniom, które ze względu na swój charakter i miejsce w procesie wydobycia dzielimy na pasywne i aktywne. Aktywne metody zapobiegania tąpaniom polegają na likwidacji naprężeń w obszarach ich koncentracji poprzez kontrolowane prowokowanie wstrząsów i tąpnięć górotworu przy wykorzystaniu robót strzałowych (grupowe strzelania urabiające, strzelania odprężające w górotworze i w filarach zdolnych do akumulacji naprężeń oraz w spągu i w stropie wyrobisk). Strzelania grupowe jako podstawowa metoda są bardzo skuteczne w warunkach kopalń miedzi. Prowokowanie zjawisk dynamicznych pozwala na kontrolowanie czasu i miejsca ich wystąpienia. W polskich kopalniach miedzi wszystkie roboty strzałowe wykonywane są pod nieobecność pracowników w rejonie eksploatacji. Dzienna ilość zarejestrowanych silnych zjawisk sejsmicznych oraz ilość uwolnionej przy tym energii potwierdzają celowość stosowania tego sposobu zapobiegania tąpaniom. Metody zapobiegania zagrożeniu tąpaniowemu opracowanie w ciągu 40 lat eksploatacji złoża miedzi są opłacalne ekonomicznie i zapewniają odpowiednią skuteczność w warunkach wysokiego poziomu zagrożenia tąpaniami.