AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE
AGH UNIVERSITY OF SCIENCE
AND TECHNOLOGY

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Geomechanical methods of rockburst prediction used in Polish coal mines - theory and practice

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Where we are

KRAKÓW
Founded in 1257
Former capitol of Poland

AGH UST history

In 1919, Józef Piłsudski, the Head of the State, inaugurated the Academy of Mining – Akademia Górnicza - AG. The first technical university in Poland.

In 1947, an internal resolution was adopted to change the name to the **Academy of Mining and Metallurgy – Akademia Górniczo-Hutnicza - AGH**

Main facts about rockburst hazard in Polish hard coal mines

- Depth of coal exploitation – 500–1,300 m, average ca. 800 m
- About 50% coal is mined from seams with rockburst hazard
- Multiples seam exploitation (10-15 seams)
- Complex of geological and mining conditions
- Influence of mining tremors on surface - objects and people
- Necessity of rockburst hazard prediction for maximum 3-year periods

Numbers of rockburst in last 5 years in Polish coal mines

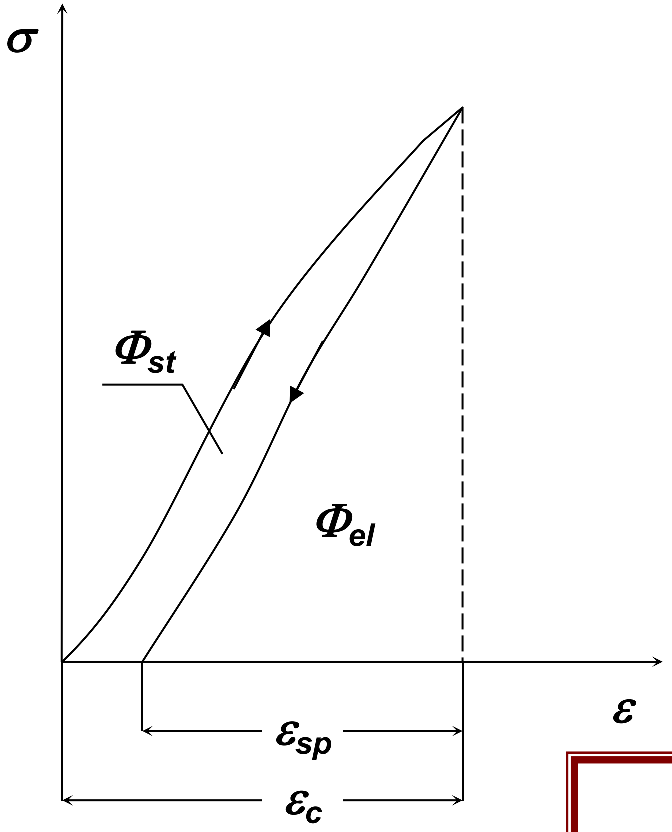
Year	No. of tremors with energy ≥ 1x10^5 J	No. of rockbursts	No. rockbursts to no. of tremors [%]
2014	1766	1	0,06
2015	1548	2	0,06
2016	1531	1	0,07
2017	1201	3	0,08
2018	1509	2	0,07

Rockburst hazard studies

- Rock mass and coal proneness to rockburst – laboratory test and empirical analysis based on lithology
- Prediction of the places with stress concentration
- The estimation of the influence of mining tremors on the surface

Rock mass and coal proneness to rockburst

Energetic rockburst index for coal W_{ET}. It's a quotient of elastic energy cumulated in a coal specimen Φ_{el} to energy used on permanent strain Φ_{st}.



$$W_{ET} = \frac{\Phi_{el}}{\Phi_{st}}$$

$W_{ET} < 2,0$ - no prone-burst coal

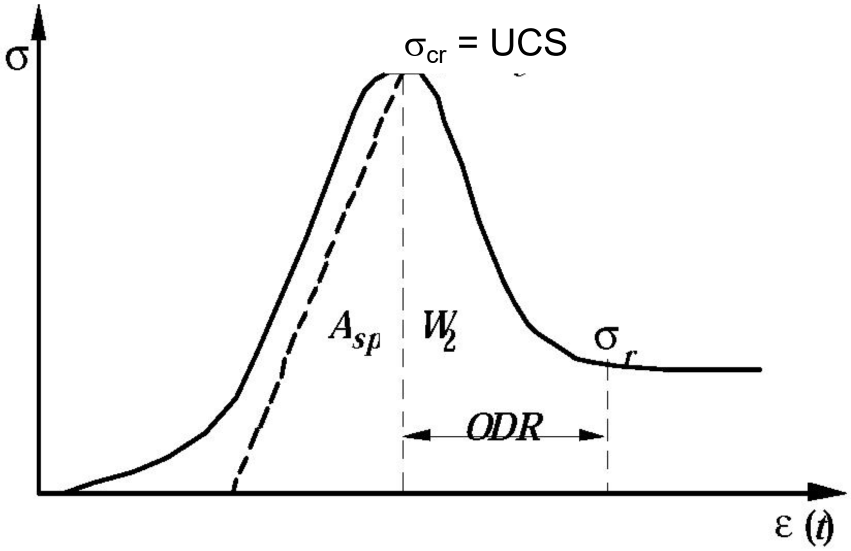
$2,0 < W_{ET} < 5,0$ - coal weak prone to rockburst

$5,0 < W_{ET}$ - coal strong prone to rockburst

(Szecówka et al. 1973)

Time of coal dynamic disintegration - ODR

The index deriving in uniaxial compression test with strain rate of 0.02/s ~1mm/s. The strain-stress characteristics is the basis of the analysis. ODR index is the time difference between the coal sample disintegration starts at σ_{cr} = *UCS* and it reaches the residual stress σ_{red}



(Kidybiński & Smołka 1988)

$$ODR = t_{\sigma_{res}} - t_{\sigma_{cr}}$$

ODR > 300ms - no prone-burst coal
50ms < ODR < 300ms - coal weak prone to rockburst
50ms > ODR - coal strong prone to rockburst

Potential elastic energy index for rocks - P_{ES}

The assessment of rock to burst under pressure can be show with **potential energy elastic strain** Φ_{el}, which can be accumulated in volume V of rock during its deformation. Based on the strength and deformation parameters derived in uniaxial compression test, energy of elastic deformation can we draw as:

$$\Phi_{el} = \frac{\sigma^2}{2E} V$$

where: $\sigma = \gamma \cdot H$ vertical stress

Max. value of energy in rock is in moment where the stress got unixal strength σ_c: $\sigma = \sigma_c$, so:

$$\Phi_{el} = \frac{\sigma_c^2}{2E} V$$

Unit energy of elastic strain Φ_{el} (for volume V=1 m^3), given in (kJ) is called as P_{ES}:

$$P_{ES} = \frac{1000\sigma_c^2}{2E} = 500\frac{\sigma_c^2}{E}$$

Classification of rocks acc. to P_{ES}

Class	Value, kJ	Rock to rockburst
I	$P_{ES} < 40$	**Rock is no prone to rockburst**
II	$40 < P_{ES} < 100$	**Rock is weak prone to rockburst**
III	$100 < P_{ES} < 200$	**Rock is high prone to to rockburst**
IV	$P_{ES} > 200$	**Rock is wery high prone to to rockburst**

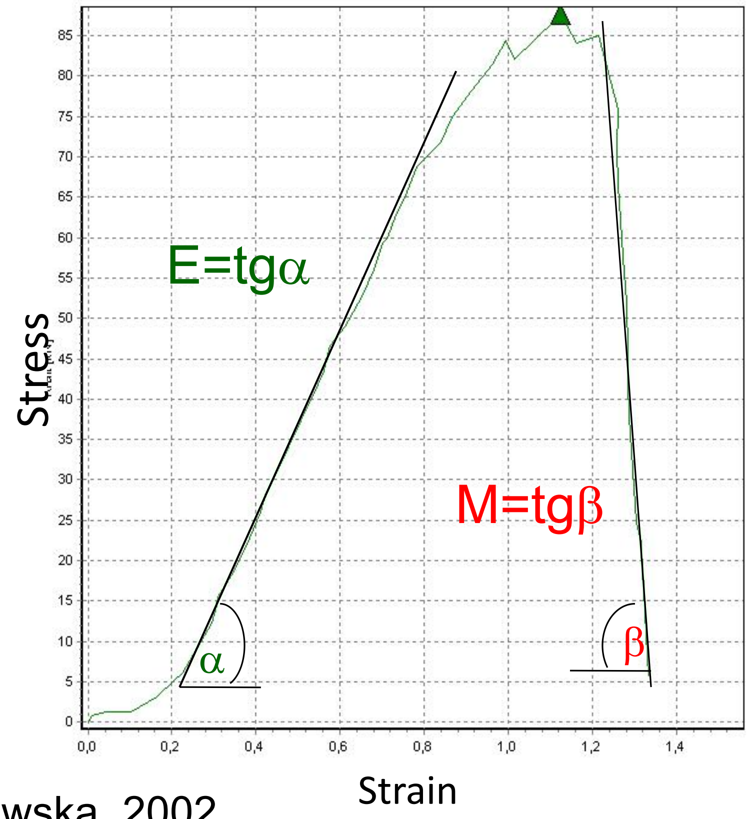
Rockburst Index for the rockmass - W_{TG}

It utilizes full stress–strain characteristic for rock specimens and post-failure behawior of coal. The configuration roof – seam – floor is analyzed, taking into consideration 100 m section in the roof and 30 m in the floor. The index W_{TG} includes geomechanical parameter for rocks: Young modulus E_{rock} for rock beds lying next to the coal seam and post-failure modulus M_c for coal.

$$W_{TG} = \frac{M_{coal}}{E_{rock}}$$

M_c - post-failure modulus for coal

E_{rock} - Young modulus for rock around seam

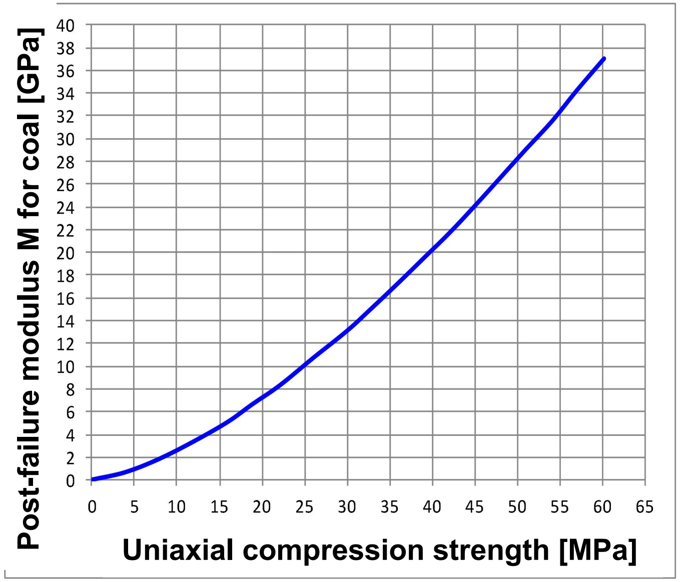


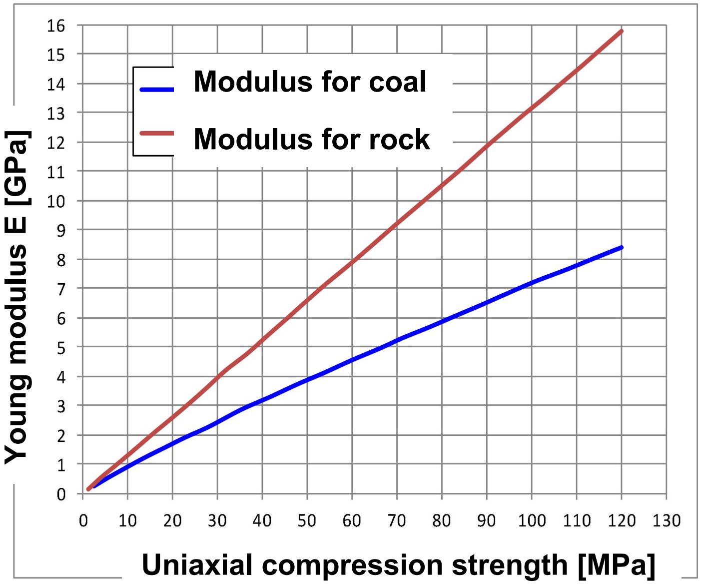
M. Bukowska, 2002

Rockburst Index for rockmass – W_{TG} the classification

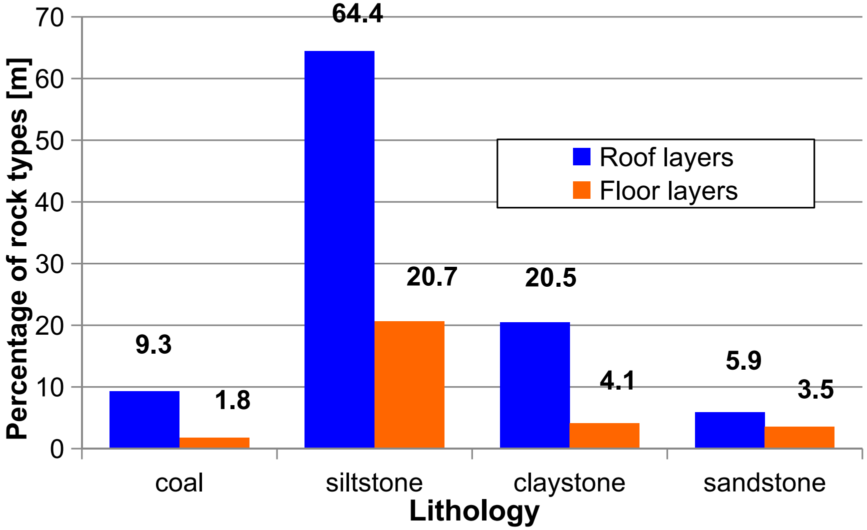
Value of index W_{TG}	Tendency to rockburst	Characteristic of mechanism damage for coal
$W_{TG} < 1.0$	configuration roof-seam – floor whithout tendency to rockburst	In this case Young modulus E_{rock} for rocks around a seam is much higher than post-failure modulus for coal M_w we can expect static damage of a seam
$1.0 < W_{TG} < 2.0$	configuration roof-seam – floor with tendency to rockburst	In this case Young modulus E_{rock} for rocks around a seam is lower than post-failure modulus for coal M_w we can expect dynamic damage of a seam. The coal „works” like a specimen in UCS test
$2.0 < W_{TG}$	configuration roof-seam – floor with a little tendency to rockburst	In this case Young modulus E_{rock} for rocks around a seam is much lower than post-failure modulus for coal M_w - we can expect static damage of a seam. The analysed composition can't cumulate elastic energy, however the rockburst is probable at big depth and if WTG is close to 2.0.

W_{TG} determination – the case





after M. Bukowska 2002



Parameters for coal:
Rc = 11,5 MPa
M = 3,22 GPa

Parameters for rock:
Rc = 31,62 MPa
E = 4,14 GPa

$$W_{TG} = M_{coal} / E_{rock}$$

$$\boxed{W_{TG} = 0,78}$$

rockmass - configuration roof-seam – floor) whithout tendency to rockburst

ROCKMASS NUMBER L_g

$$L_g = \frac{1}{2}\left(L_{st} + L_{sp}\right)$$

L_{st} – number for the roof
L_{sp} – number for the floor

L_{st} – number for the roof

$$L_{st} = \Sigma h_i \cdot \gamma_i \Rightarrow L_{st} = 1{,}00\,s + 0{,}62\,c + 0{,}29\,s + 0{,}31\,c + 0{,}04\,g + 0{,}01\,ff$$

sum of litology for type of rock (Σ100 m)

factor of cohesion reduction depends on a type of rock

s – sandstone
c – claystone
s – siltstone
c – coal
g – goaf
ff – fully filling (f.e. sand)

L_{sp} – number for the floor

$$L_{sp} = \frac{100}{30}\Sigma h_i \cdot \gamma_i$$

100/30 due to 30 m for floor rock

EXPERIENCE: THE ROCKBURST HAPPENED FOR ROCKMASS NUMBER $L_g > 50$

For previous data:

$$L_g = \frac{1}{2}\left[(1.00\cdot 5.9 + 0.62\cdot 20.5 + 0.29\cdot 64.4 + 0.31\cdot 9.3) + \frac{100}{30}(1.00\cdot 3.5 + 0.62\cdot 4.1 + 0.29\cdot 20.7 + 0.31\cdot 1.8)\right]$$

$$= \frac{1}{2}\left[(5.9 + 12.7 + 18.7 + 2.9) + \frac{10}{3}(3.5 + 2.5 + 6.0 + 5.6)\right] = \frac{1}{2}\left(40.2 + \frac{10\cdot 17.6}{3}\right) = \boxed{49.44}$$

„*GEO*” system for rockburst proneness evaluation (after Bukowska)

Factor	**Rank (R)**	**Class**	**Weight (W)**		**Range *GEO* *pts.***
			pts.	symbol	
Depth	$R_G = 3$	300 - 400 m 400 – 550 m 550 – 700 m > 700 m	1 – 7	W_G	GEO_G 3 - 21
Distance from the coal seam to a strong bed	$R_o = 1$	No strong beds around < 50 m 50 - 100 m	0 – 12	W_O	GEO_O 0 - 12
Number of rockmass L_g	$R_L = 3$	< 40 40 – 50 50 – 80 > 80	0 – 7	W_L	GEO_L 0 - 21
Rockburst index for rockmass W_{TG}	$R_T = 3$	< 0,99 0,99 – 1,00 1,00 – 1,99 1,99 – 2,00 > 2,00	0 – 8	W_T	GEO_T 0 - 24
Factor of kinetic energy for rock mass W_{Ek}	$R_E = 3$	< 1,00 1,00 – 2,00 2,01 – 19,00 19,01 – 20,00 > 20,00	0 – 8	W_E	GEO_E 0 - 24
Thickness of the coal seam	$R_M = 2$	< 1,0 m 1,0 – 4,5 m > 4,5 m	0 – 6	W_M	GEO_M 0 - 12
				Total	**3 - 114**

$$W_{EK} = \frac{E_{kg}}{E_{kp}},$$

where E_{kg} is the kinetic (specific) energy of the rock mass; E_{kp} is the kinetic (specific) energy of the coal seam.

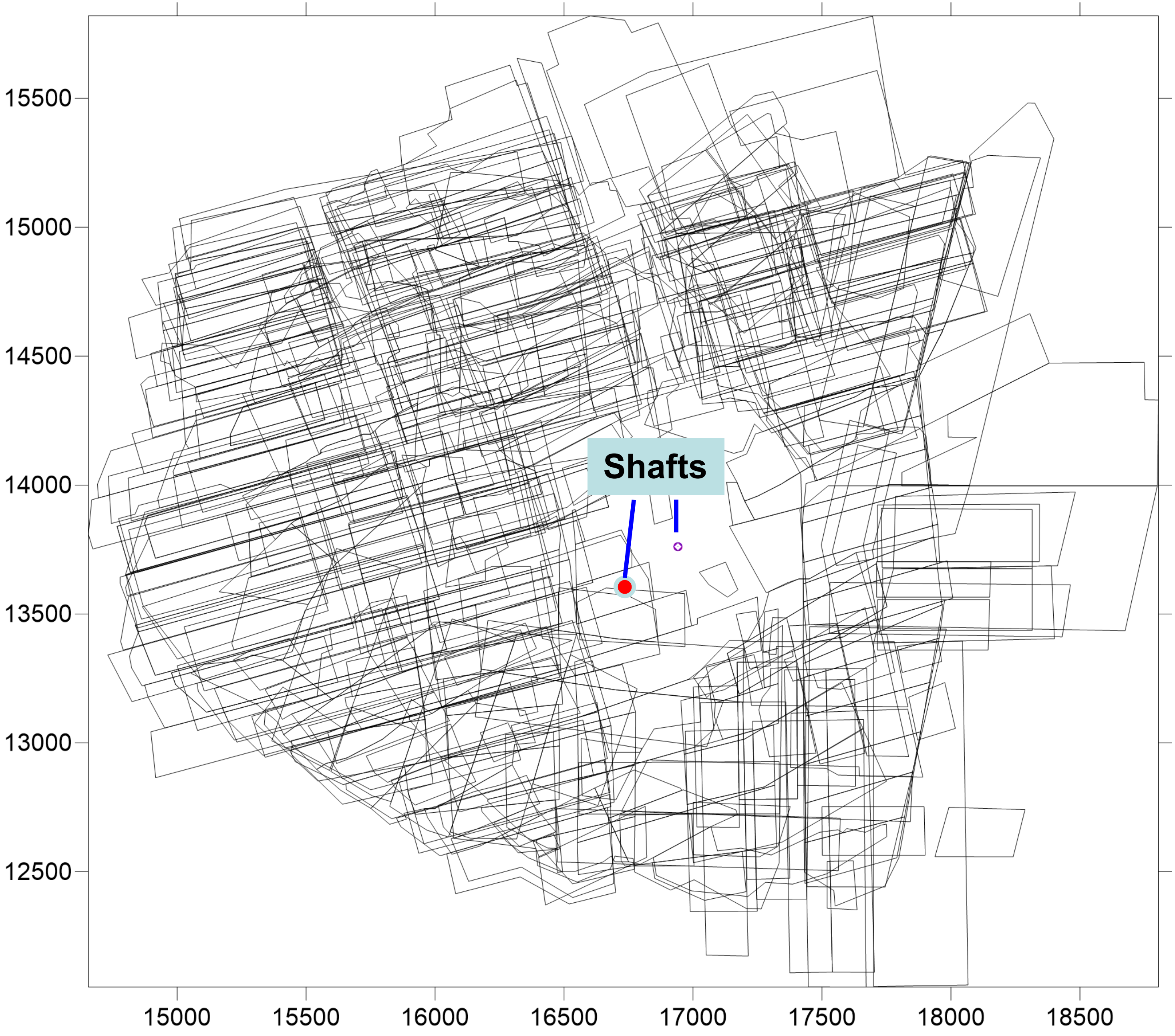
„*GEO*” system for rockburst proneness evaluation – the classification

The analysis includes roof layers up to 100 m above a seam and floor layers up to 30 m below the seam. The range of „GEO” system is from 3 to 114 points.
Rockmass proneness to rockburst is described as follows:

The assesement of natural rockmass proneness to rockbursts on the basis on geological and geomechanical factors	Indicator „*GEO*”
Rockmass no prone to rockburst	**<58**
Rockmass weak prone to rockburst	**58 ÷ 80**
Rockmass strong prone to rockburst	**>80**

Prediction of the places with stress concentration

Example of multiple seam exploitation



Dymek solutions which used analysis of the deformation of the elastic half-space

Each mined and planned longwall panel is rectangle (dimensions 2*a* and 2*b*). The rock mass is isotropic and continuous. The state of displacement for each „*i*” rectangle area is calculated using following boundary conditions:

$$w_i(x, y, z=0) = \begin{Bmatrix} w_{oi} = const > 0 \\ 0 \end{Bmatrix} \qquad \begin{matrix} |x| \le a \quad i \quad |y| \le b \\ |x| > a \quad i \quad |x| > b \end{matrix}$$

Components of the displacement:

$$u_i(x,y,z) = \frac{-w_{oi}}{2\pi(3-4\nu)} \begin{Bmatrix} \dfrac{z^2}{z^2+(x+a)^2}\left[\dfrac{y+b}{\sqrt{(x+a)^2+(y+b)^2+z^2}} - \dfrac{y-b}{\sqrt{(x+a)^2+(y-b)^2+z^2}}\right] - \\ \dfrac{z^2}{z^2+(x+a)^2}\left[\dfrac{y+b}{\sqrt{(x-a)^2+(y+b)^2+z^2}} - \dfrac{y-b}{\sqrt{(x-a)^2+(y-b)^2+z^2}}\right] \end{Bmatrix}$$

$$v_i(x,y,z) = \frac{-w_{oi}}{2\pi(3-4\nu)} \begin{Bmatrix} \dfrac{z^2}{z^2+(y+b)^2}\left[\dfrac{x+a}{\sqrt{(x+a)^2+(y+b)^2+z^2}} - \dfrac{x-a}{\sqrt{(x-a)^2+(y+b)^2+z^2}}\right] - \\ \dfrac{z^2}{z^2+(y-b)^2}\left[\dfrac{x+a}{\sqrt{(x+a)^2+(y-b)^2+z^2}} - \dfrac{x-b}{\sqrt{(x-a)^2+(y-b)^2+z^2}}\right] \end{Bmatrix}$$

Components of the displacement (cont.):

$$w_i(x,y,z)=\frac{w_{oi}}{2\pi}\left\{\begin{array}{l} arctg\left(\dfrac{(x+a)(y+b)}{z\sqrt{(x+a)^2+(y+b)^2+z^2}}\right)-arctg\left(\dfrac{(x-a)(y+b)}{z\sqrt{(x-a)^2+(y+b)^2+z^2}}\right)+\\ arctg\left(\dfrac{(x-a)(y-b)}{z\sqrt{(x-a)^2+(y-b)^2+z^2}}\right)-arctg\left(\dfrac{(x+a)(y-b)}{z\sqrt{(x+a)^2+(y-b)^2+z^2}}\right)+ \end{array}\right\}$$

$$+\frac{z}{3-4\nu}\left[\left(\begin{array}{l} \dfrac{(x+a)(y+b)}{\left(z^2+(x+a)^2\right)\left(z^2+(y+b)^2\right)}\sqrt{(x+a)^2+(y+b)^2+z^2}+\dfrac{z^2}{\sqrt{(x-a)^2+(y+b)^2+z^2}}+\\ \dfrac{(x-a)(y-b)}{\left(z^2+(x-a)^2\right)\left(z^2+(y+b)^2\right)}\sqrt{(x-a)^2+(y+b)^2+z^2}+\dfrac{z^2}{\sqrt{(x+a)^2+(y+b)^2+z^2}}+\\ \dfrac{(x-a)(y-b)}{\left(z^2+(x-a)^2\right)\left(z^2+(y-b)^2\right)}\sqrt{(x-a)^2+(y-b)^2+z^2}+\dfrac{z^2}{\sqrt{(x+a)^2+(y-b)^2+z^2}}+\\ \dfrac{(x+a)(y-b)}{\left(z^2+(x+a)^2\right)\left(z^2+(y-b)^2\right)}\sqrt{(x+a)^2+(y-b)^2+z^2}+\dfrac{z^2}{\sqrt{(x+a)^2+(y-b)^2+z^2}} \end{array}\right)\right]$$

Having the components of displacement vector [u] = {u, v, w} from geometrical equtions we calculate components of the strain:

$$[\varepsilon] = \{\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \gamma_{xy}, \gamma_{yz}, \gamma_{xz}\},$$

Then, from Hooke's law we calculate elastic stress tensor:

$$[\sigma] = \{\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xy}, \tau_{yz}, \tau_{xz}\}$$

The displacements change in time due to stress relaxation, so the stress tensor after time t_{oi} is amounted to:

$$\mathbf{T}_\sigma(\mathbf{t}_{oi}) = \chi(\Delta \mathbf{t}_{oi})\cdot \mathbf{T}_\sigma$$

where

$\mathbf{T}_\sigma(\mathbf{t}_{oi})$ - stress tensor in given point after time t_{oi} for *i* mined area ,
$\mathbf{T}_\sigma$ - stress tensor in time t = 0 for *i* mined area ,
Δt_{oi} - time period between time of *i* area was mined and analysed time,
i - number of mined area ,
$\chi(\Delta \mathbf{t}_{oi})$ - factor of stress relaxation for *i* mined area.

For Silesia Coal Basin the best model for describing relaxation stress is according with Maxwell model. Factor of relaxation state of stress could be described as:

$$\chi(\Delta \mathrm{t}_{\mathrm{oi}}) = e^{\frac{-G_M}{\eta_M}\Delta t_0}$$

where:

Δt_{oi}	- time period beetwen time of *i* area was mined and analysed time
G_M	- rock mass modulus of elasticity for Maxwell model (usually: 1-7 GPa),
η_M	- rock mass viscosity of Maxwell model (usually: 10-70 GPa·s).

Vertical stress concentration factor is described as:

$$\alpha = \frac{\sigma_z(x, y, z)}{p_z}$$

where:

$\sigma_z(x,y,z)$	- vertical stress in given point, MPa
p_z	- vertical primary stress in given point, MPa.

Vertical stress concentration factor

Depending on the value of vertical stress concentration factor α, the stress concentration zones in the rockmass can be identify,

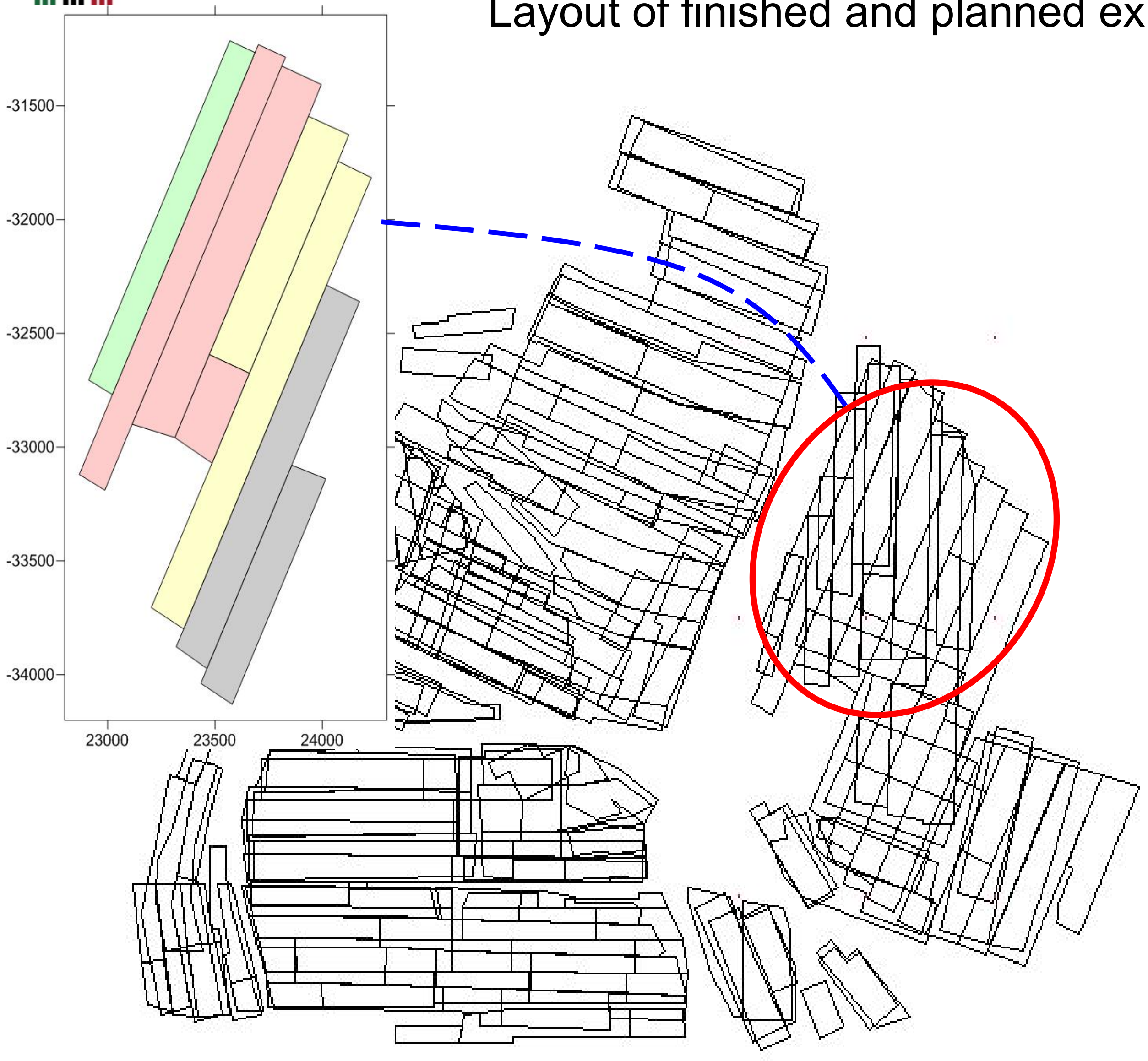
where $\alpha \leq$ 1.0 shows released zone,

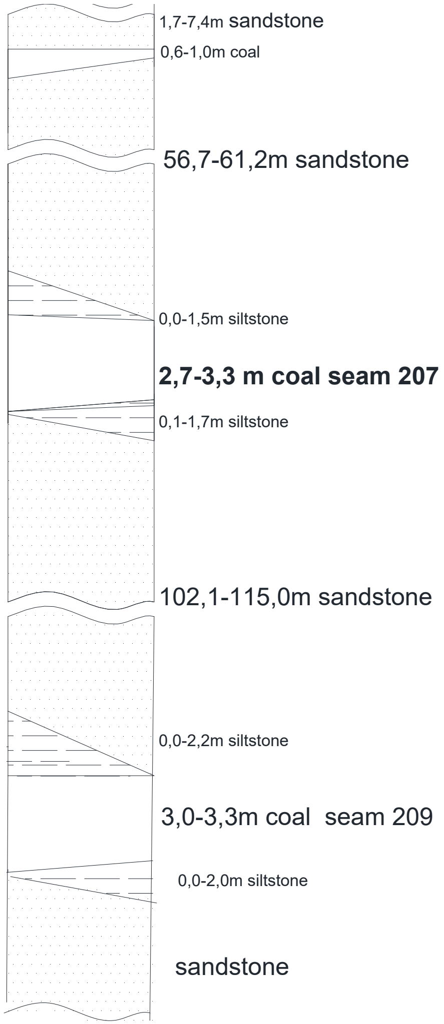
and $\alpha >$ 1,0 shows the stress concentration zone.

- $\alpha \leq 1,0$ - released zone
- $1,0 < \alpha \leq 1,5$ - zone of low stress concentration:
- $1,5 < \alpha \leq 2.0$ - zone of medium stress concentration
- $2,0 < \alpha \leq 3,0$ - zone of high stress concentration
- $\alpha > 3,0$ - zone of very high stress concentration

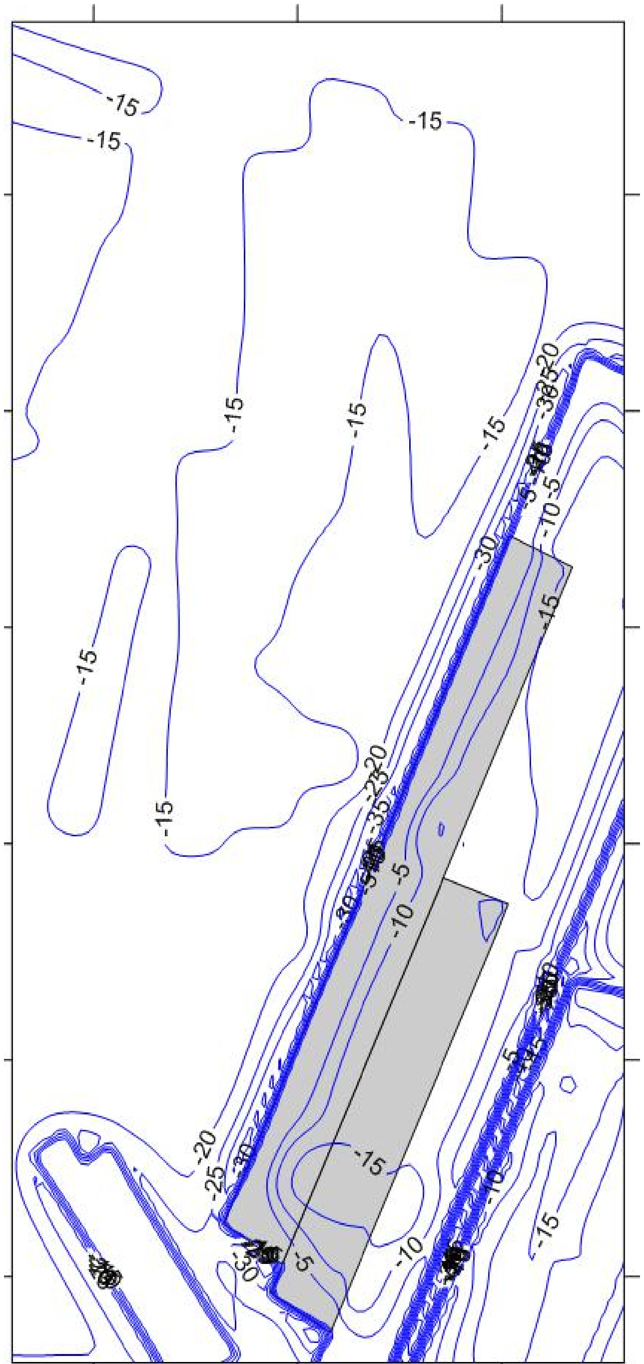
The case study from mine „X”

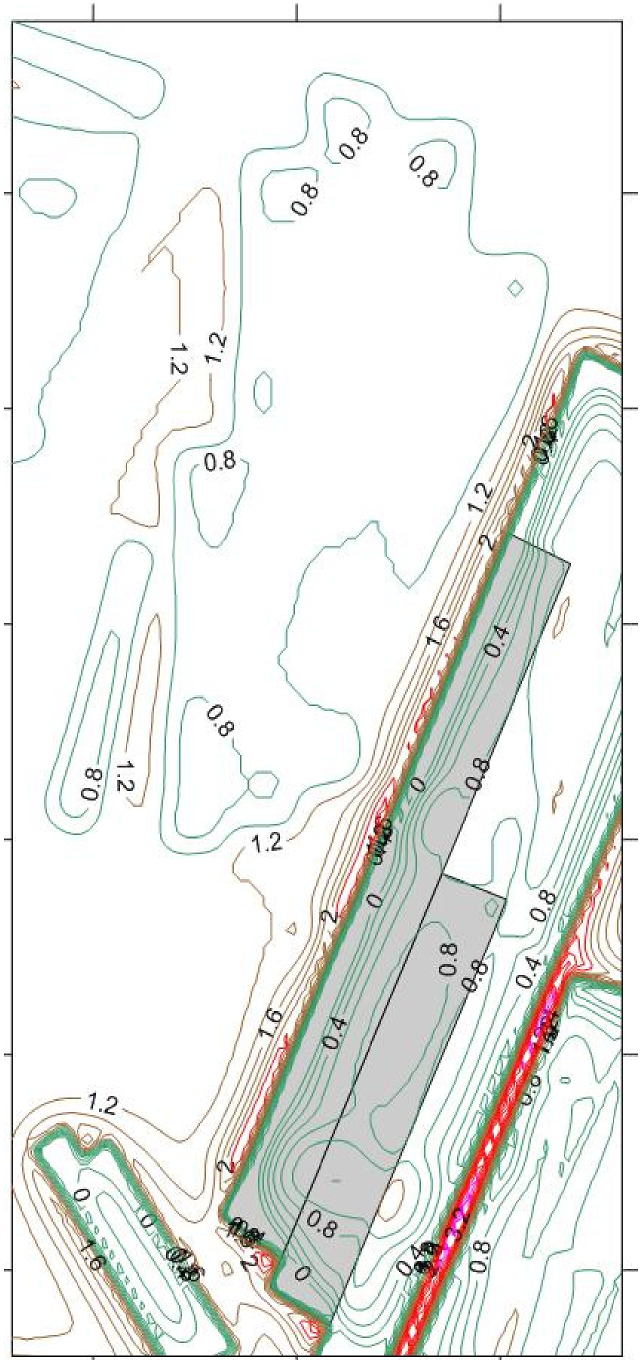
Layout of finished and planned exploitation



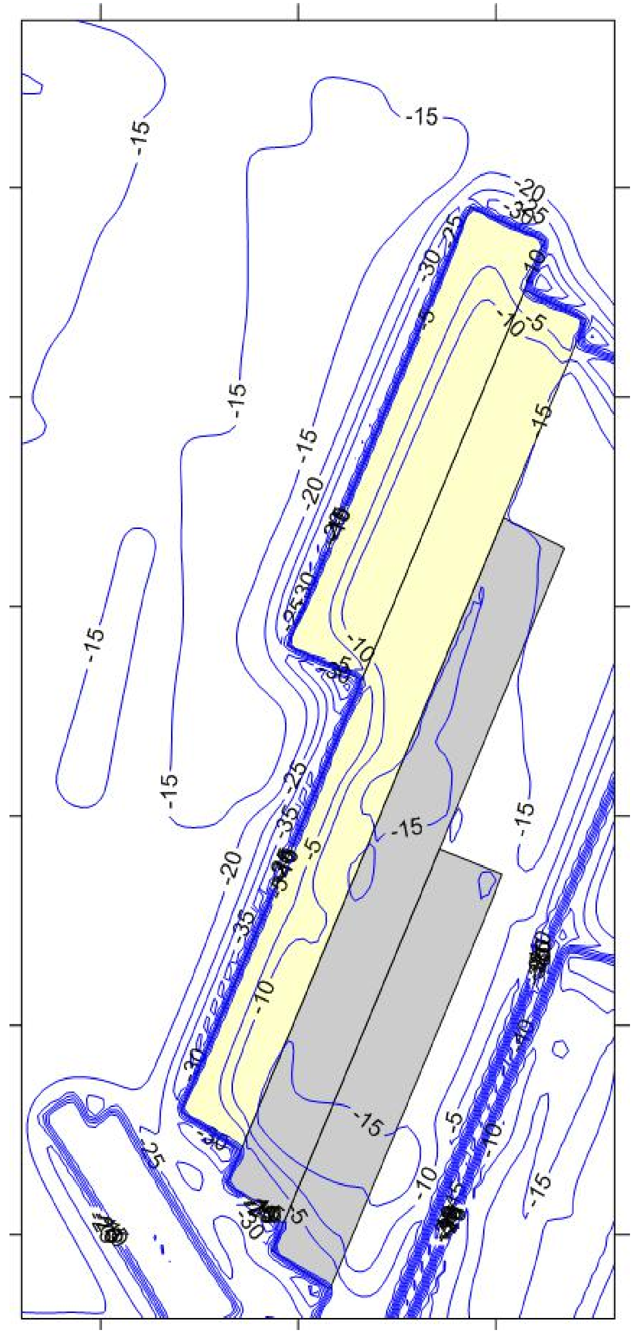


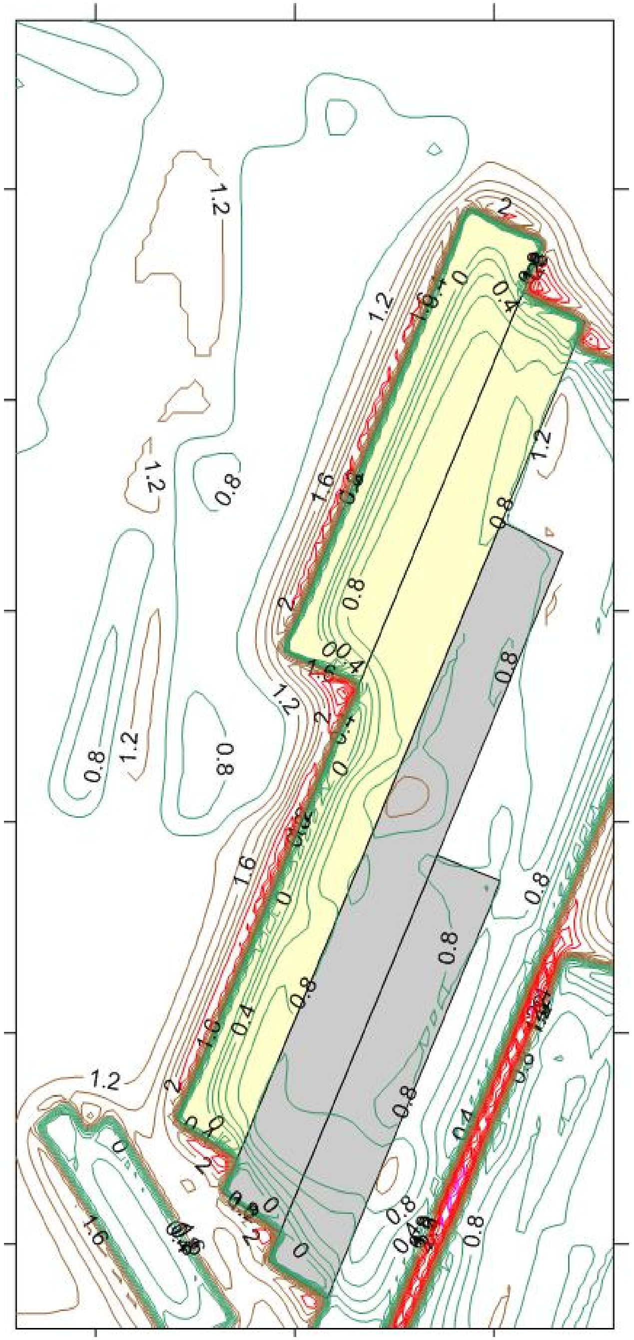
2016 - Vertical stress and stress concentrations



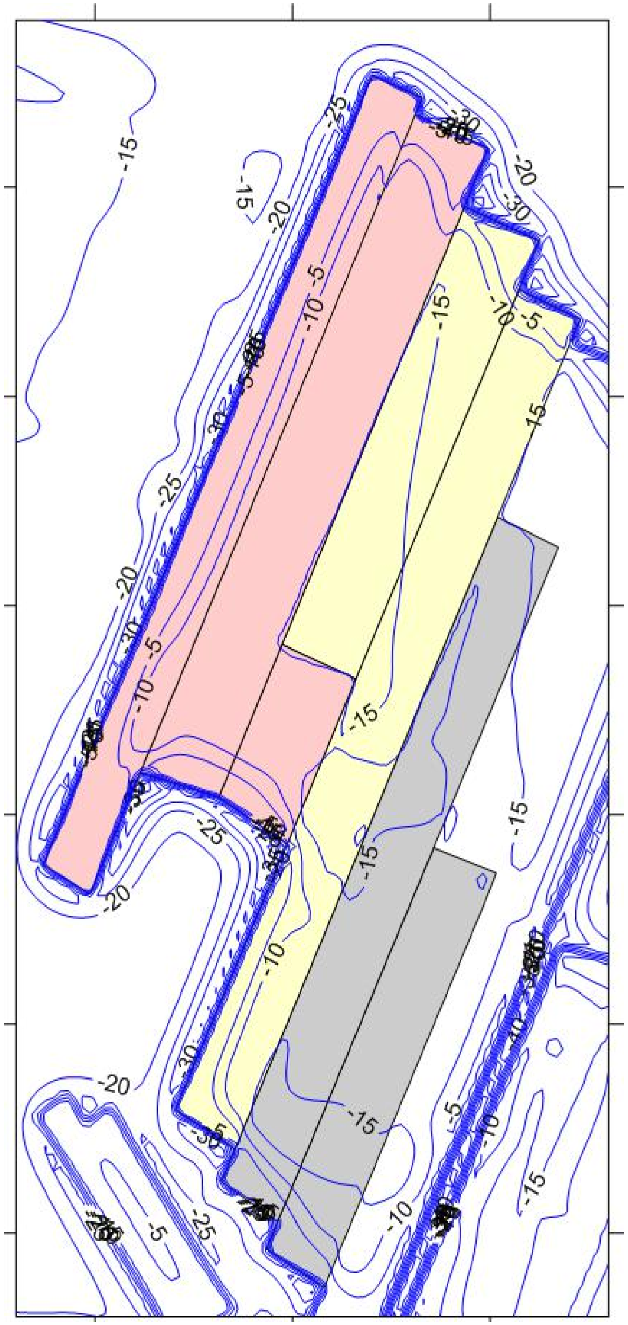


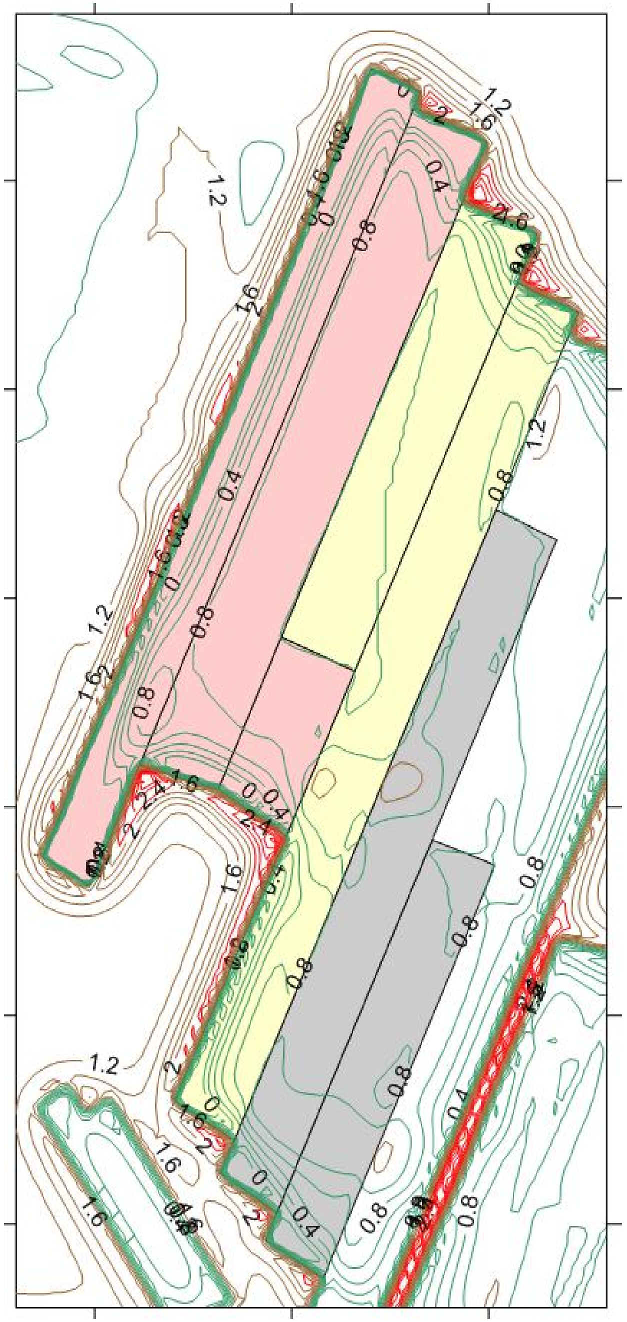
2017 - Vertical stress and stress concentrations



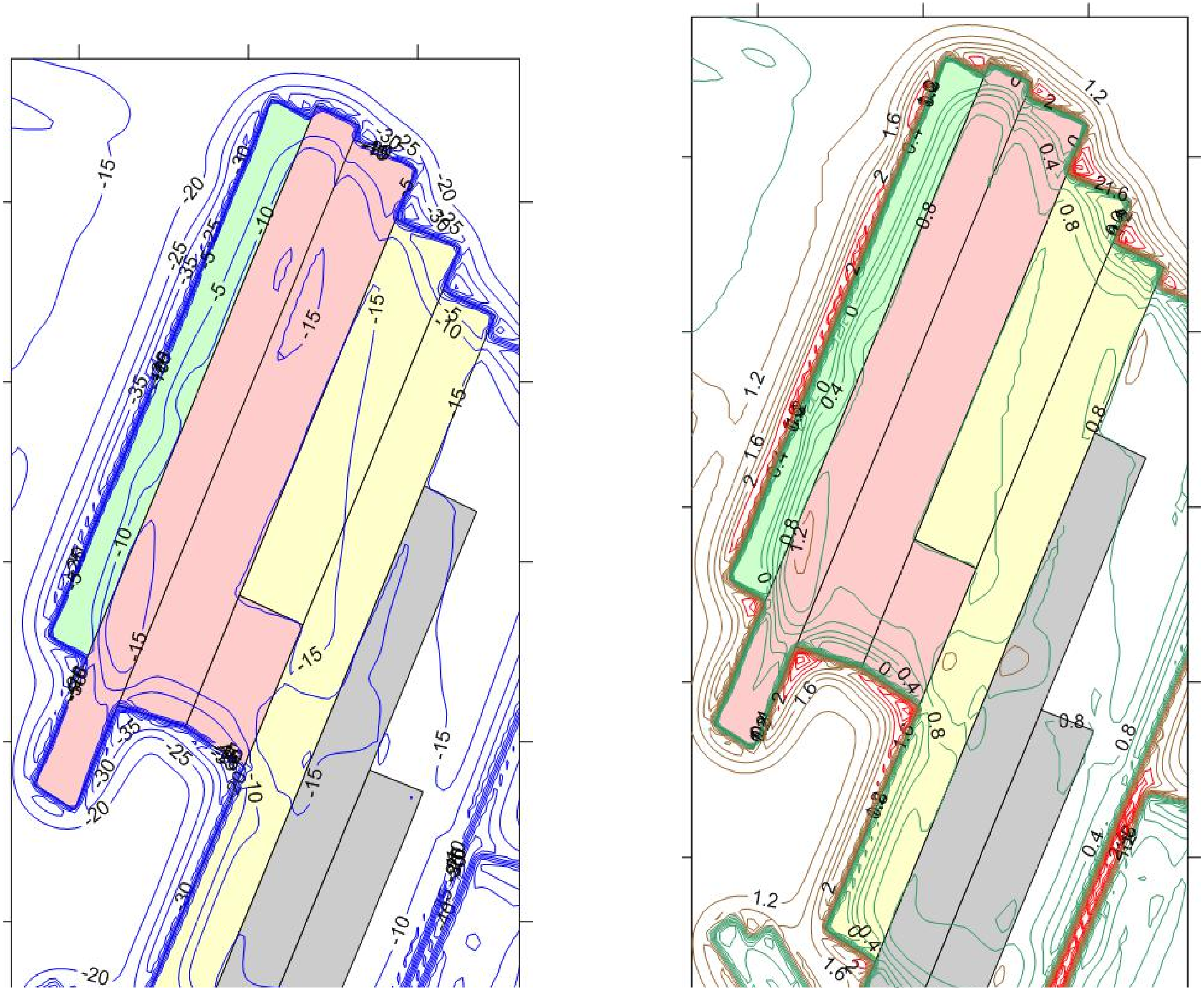


2018 - Vertical stress and stress concentrations





2019 - Vertical stress and stress concentrations

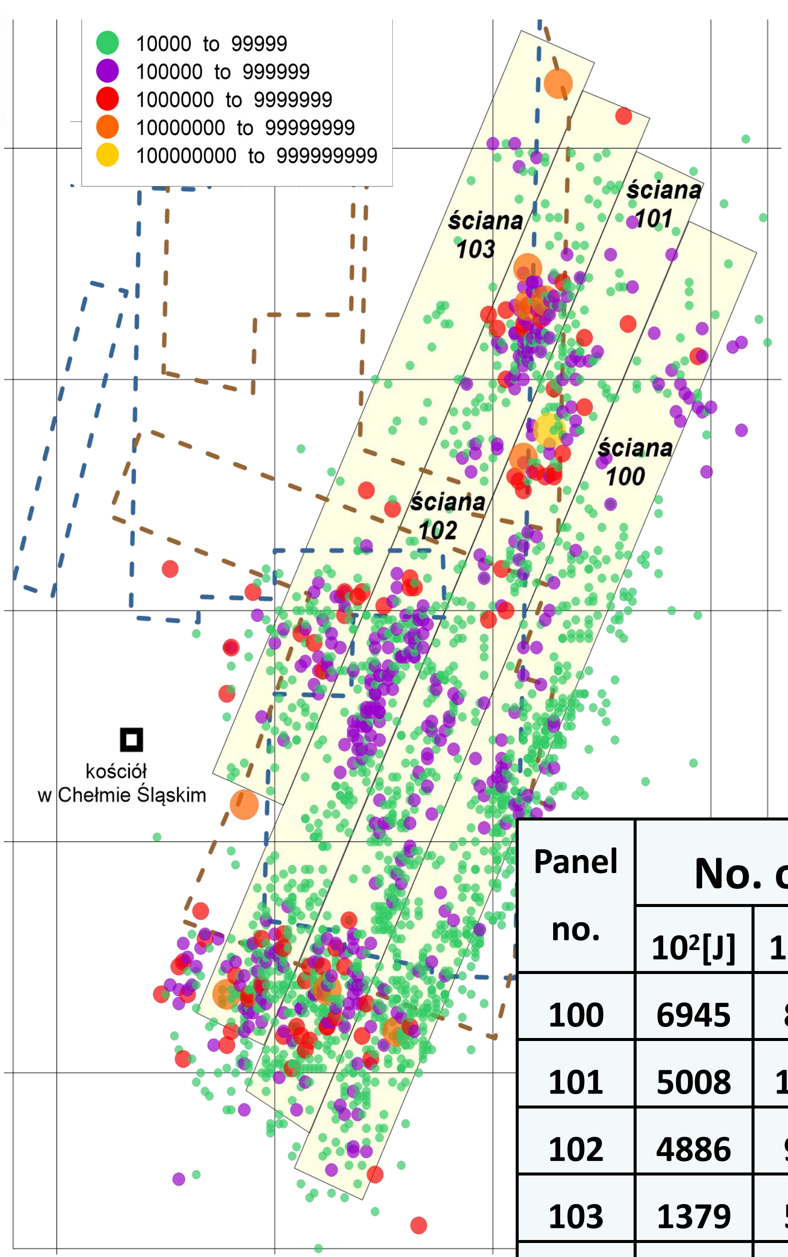


Prediction:

Maximum value of mining tremors: 7⁎10^{7} J,
very seldom in the areas next to the mining edges of above mined seam – 4⁎10^{8} J

Layout and numbers of tremors

(From 2016 to May 2018)



Panel no.	No. of tremors with the given energy							Total
	10^2[J]	10^3[J]	10^4[J]	10^5[J]	10^6[J]	10^7[J]	10^8[J]	
100	6945	854	581	86	14	2	0	8482
101	5008	1010	460	112	28	3	1	6622
102	4886	923	409	141	29	3	0	6391
103	1379	504	166	37	9	1	0	2096
Sum	18218	3291	1616	376	80	9	1	23591

The estimation of the influence of mining tremors on the surface

Ground acceleration on surface

If we register the maximum value of seismic energy, we can calculate the component of the **horizontal acceleration** of vibration on surface:

$$\log a = a_1 \log E + a_2 \log R + a_3 + \varepsilon$$

where:

a – maximum component of the horizontal acceleration of vibration on surface [m/s^2],
E – energy of mining tremor [J],
R – hypocenter distance [m],

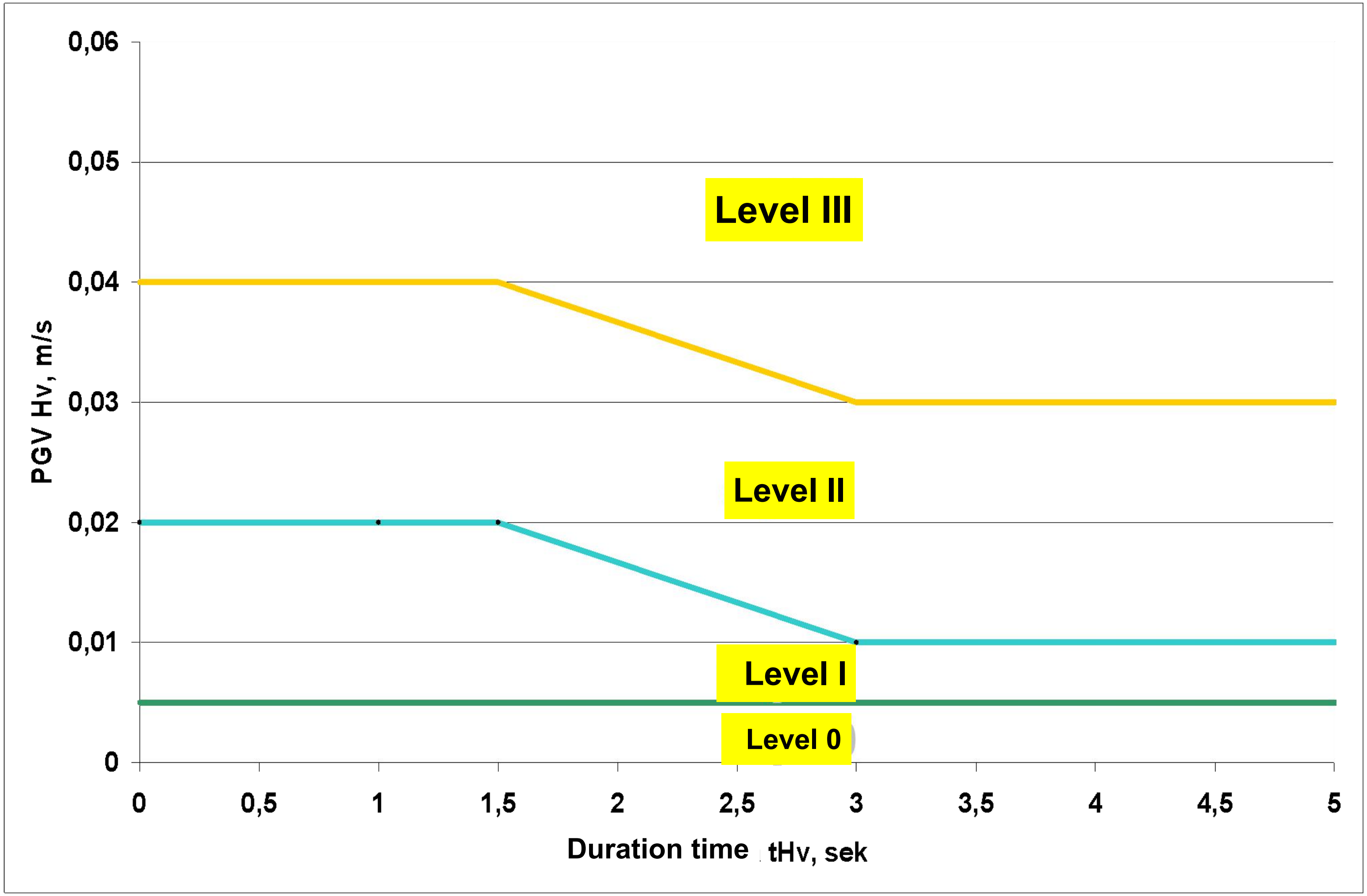
$$R = \sqrt{r^2 + h^2}$$

r – epicentral distance [m],
h – average depth of tremors in analysed area [m],
a_i – parameters of model regresion,
ε – random component.

The similar relationship we can show for horizontal velocity of ground particles

THE SCALE OF MINING TREMORS IMPACT ON THE SURFACE IN THE UPPER SILESIA COAL BASIN – POLAND

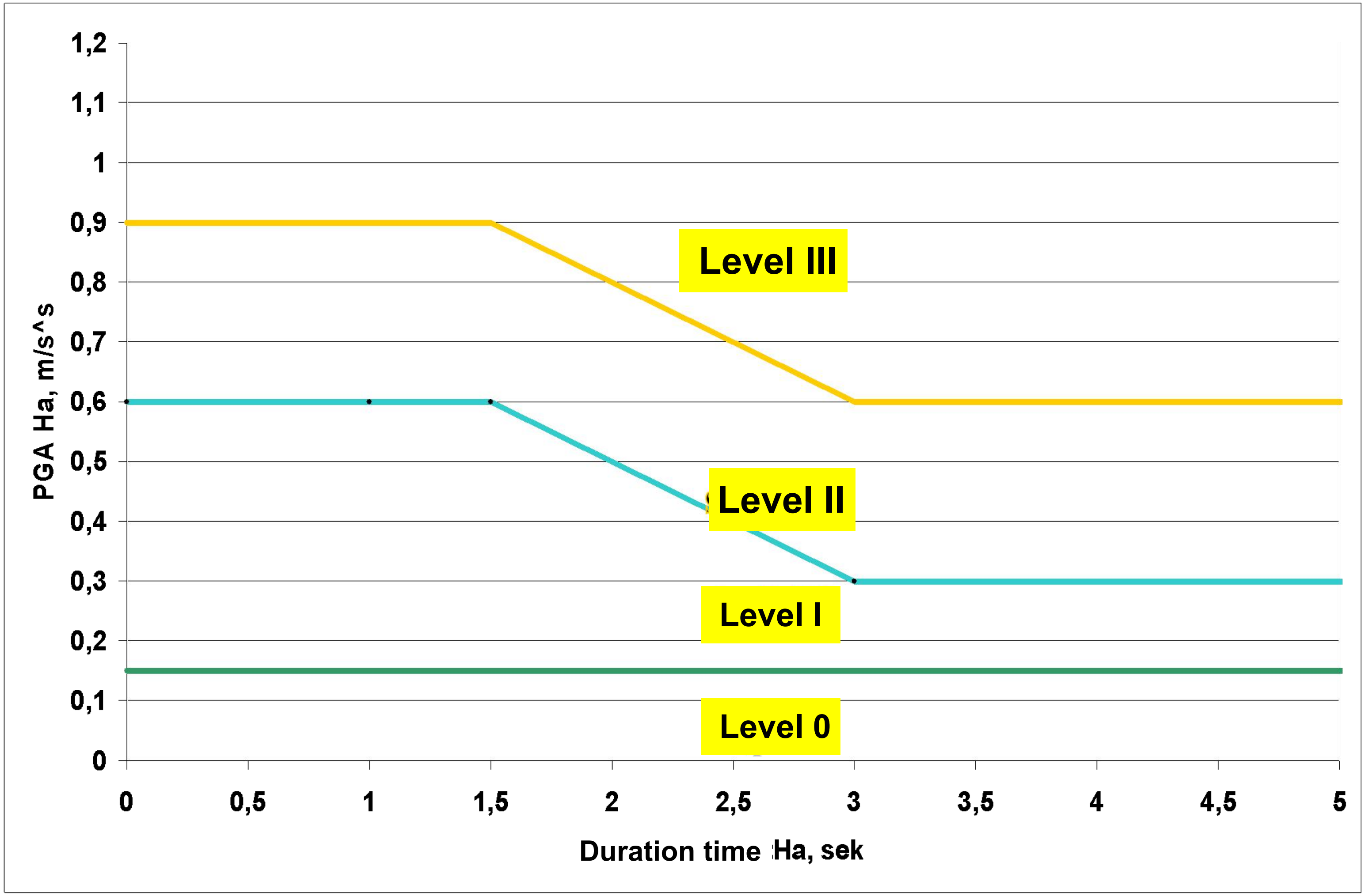
for velocity



Mutke et. al. 2008

THE SCALE OF MINING TREMORS IMPACT ON THE SURFACE IN THE UPPER SILESIA COAL BASIN – POLAND

for accelerations



Definitions of intensity levels:

Level 0

Tremors causing no damage in buildings. Vibrations not felt by people or slightly felt by people.

Level I

Tremors not causing damage to buildings. Open windows and doors may get closed without man’s action. Furniture may vibrate and hanging objects may swing. In single cases existing cracks or fissures may get larger. Tremors may be strongly perceptible at the surface, especially on high storeys.

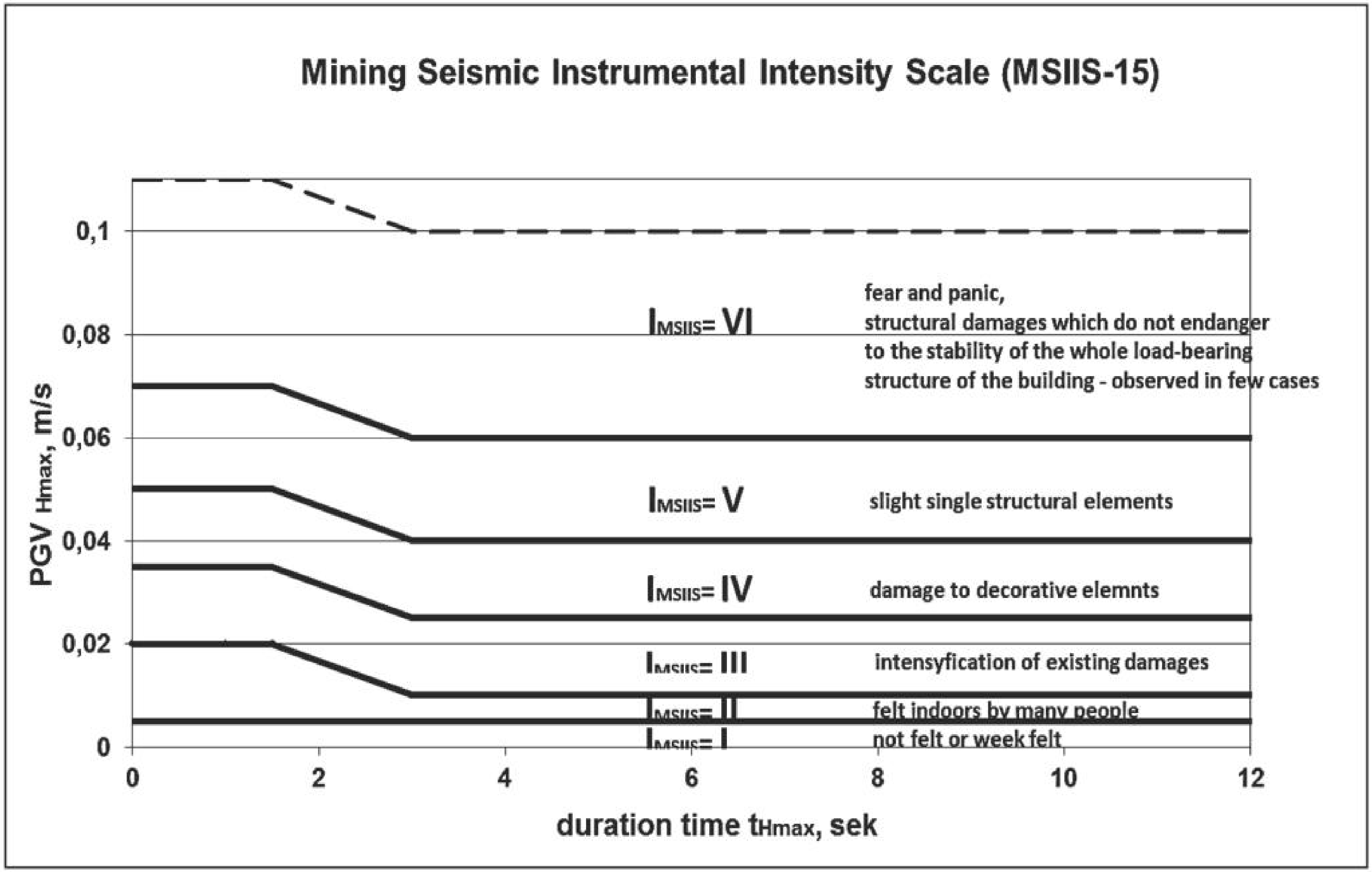
Definitions of intensity levels:

Level II

In this zone consequences described in level I may occur and vibrations capable of causing increase of the existing damage, i.e.: lengthening existing cracks and fissures, falling off small fragments of loosened inside and outside plaster, etc., in at most 5% of population of buildings covered by this level of intensity. Furniture may vibrate and hanging objects may swing. Tremors may be strongly perceptible at the surface, as in the buildings as outdoors. Observers feel a strong shaking or racking of the whole building.

Level III

Level III is weakly documented with measurement data and empirical experiments. In this zone there may occur consequences included in the description of level II and vibrations that may cause first damage to non-load-bearing elements of buildings, i.e.: cracks of inside and outside plaster, slight cracks of glazed tiles, slight cracks around the frames of windows and doors, loosening bricks of brick chimneys etc., in at most 5% of population of buildings. Furniture may be shifted. Slight damage possessions is possible. Vibrations of this intensity may wake sleeping people up. Many people get frightened during these vibrations. A few persons lose their balance, especially on upper floors.



MUTKE / CHODACKI / MUSZYŃSKI / KREMERS / FRITSCHEN, 2015

MSIIS-15 – verification results in Polish part of Upper Silesia

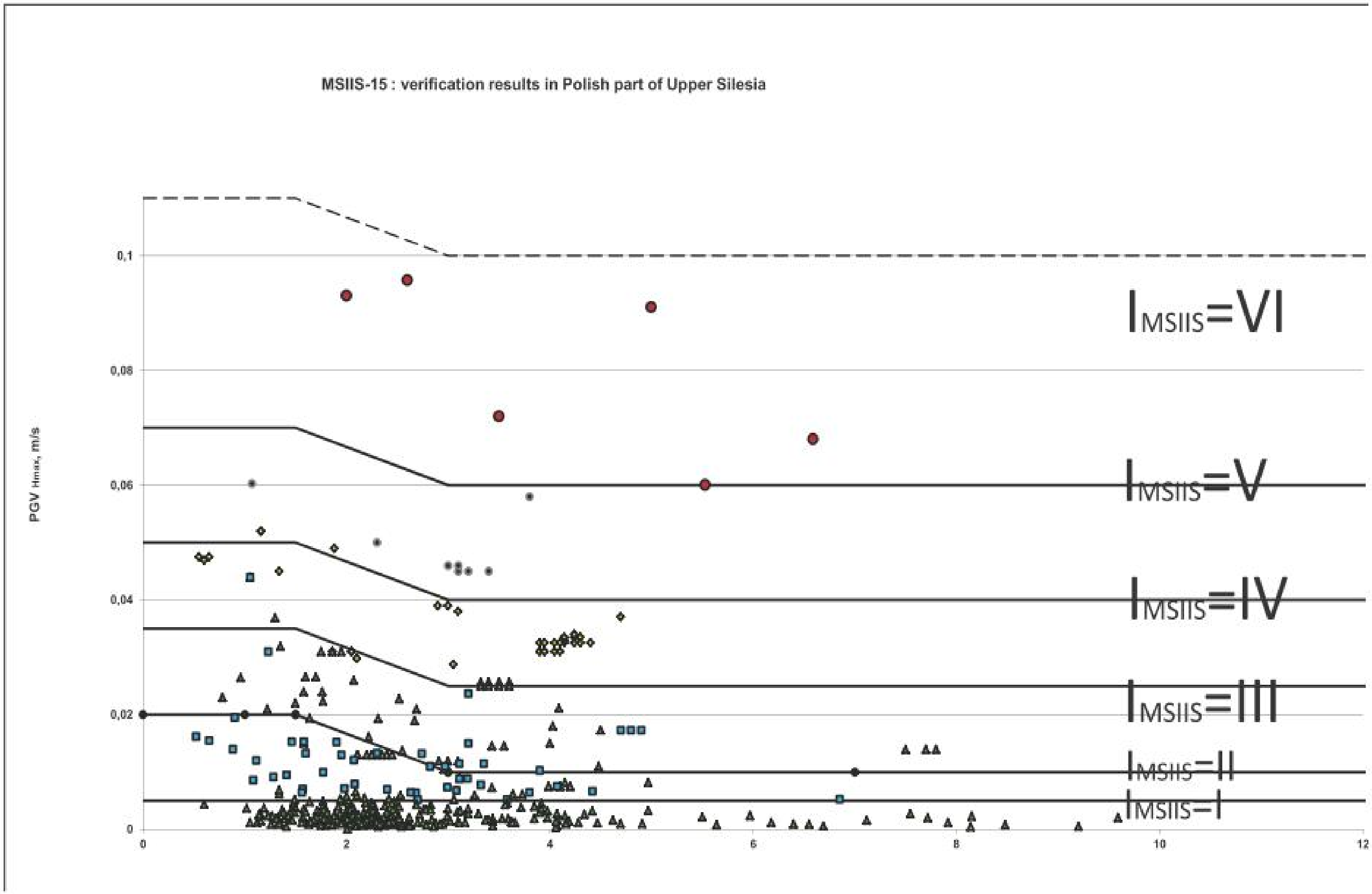
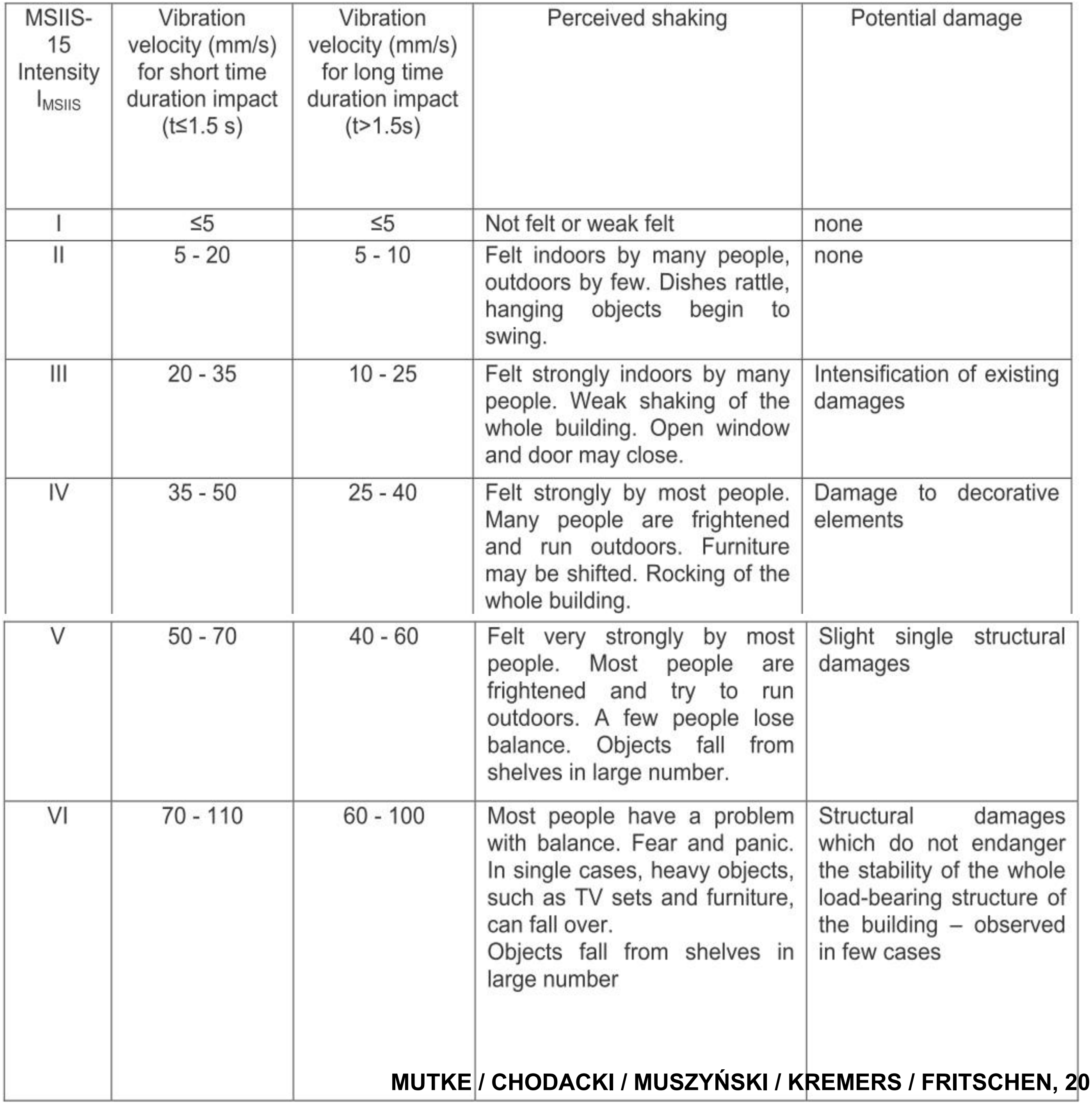


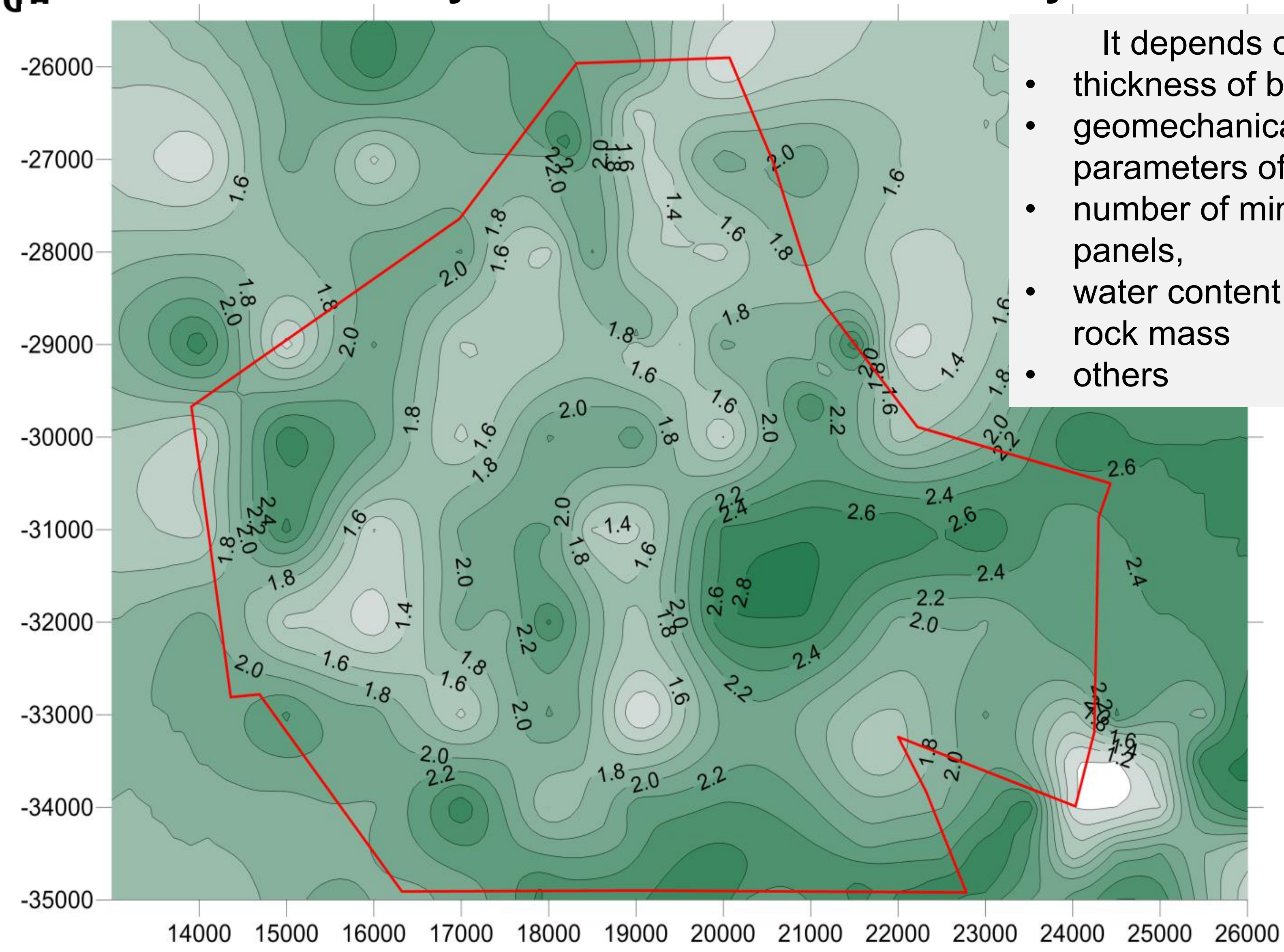
Figure 3: Results of verification MSIIS-15 scale on the basis of seismic and macroseismic observation from Upper Silesia Coal Basin – Poland



MSIIS-15 Intensity I_{MSIIS}	Vibration velocity (mm/s) for short time duration impact (t≤1.5 s)	Vibration velocity (mm/s) for long time duration impact (t>1.5s)	Perceived shaking	Potential damage
I	≤5	≤5	Not felt or weak felt	none
II	5 - 20	5 - 10	Felt indoors by many people, outdoors by few. Dishes rattle, hanging objects begin to swing.	none
III	20 - 35	10 - 25	Felt strongly indoors by many people. Weak shaking of the whole building. Open window and door may close.	Intensification of existing damages
IV	35 - 50	25 - 40	Felt strongly by most people. Many people are frightened and run outdoors. Furniture may be shifted. Rocking of the whole building.	Damage to decorative elements
V	50 - 70	40 - 60	Felt very strongly by most people. Most people are frightened and try to run outdoors. A few people lose balance. Objects fall from shelves in large number.	Slight single structural damages
VI	70 - 110	60 - 100	Most people have a problem with balance. Fear and panic. In single cases, heavy objects, such as TV sets and furniture, can fall over. Objects fall from shelves in large number	Structural damages which do not endanger the stability of the whole load-bearing structure of the building – observed in few cases

MUTKE / CHODACKI / MUSZYŃSKI / KREMERS / FRITSCHEN, 2015

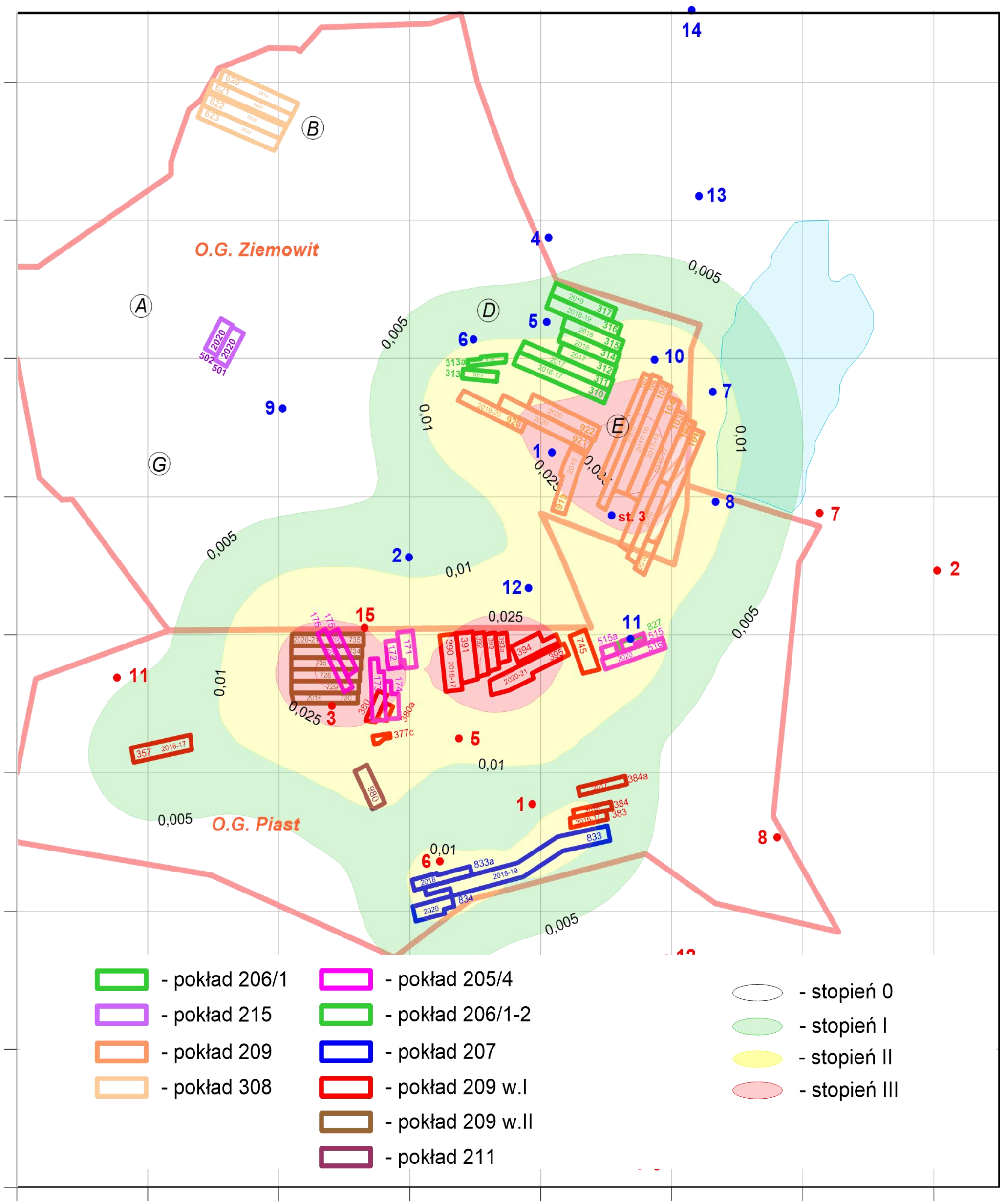
Amplification of vibrations - the factor determining the amplification or attenuation of vibrations by overburden – the case study



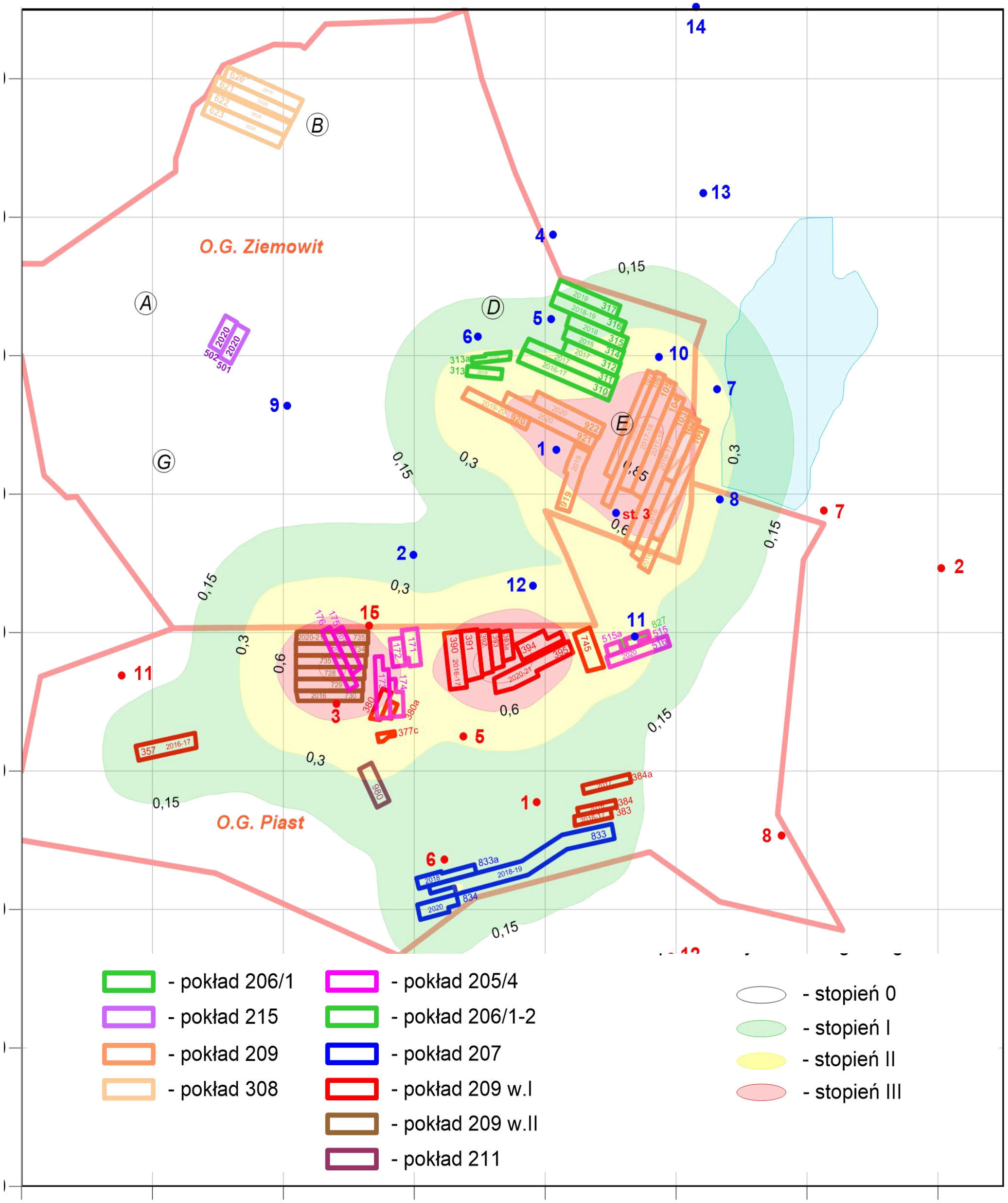
It depends on:

- thickness of beds;
- geomechanical parameters of beds,
- number of mined panels,
- water content in the rock mass
- others

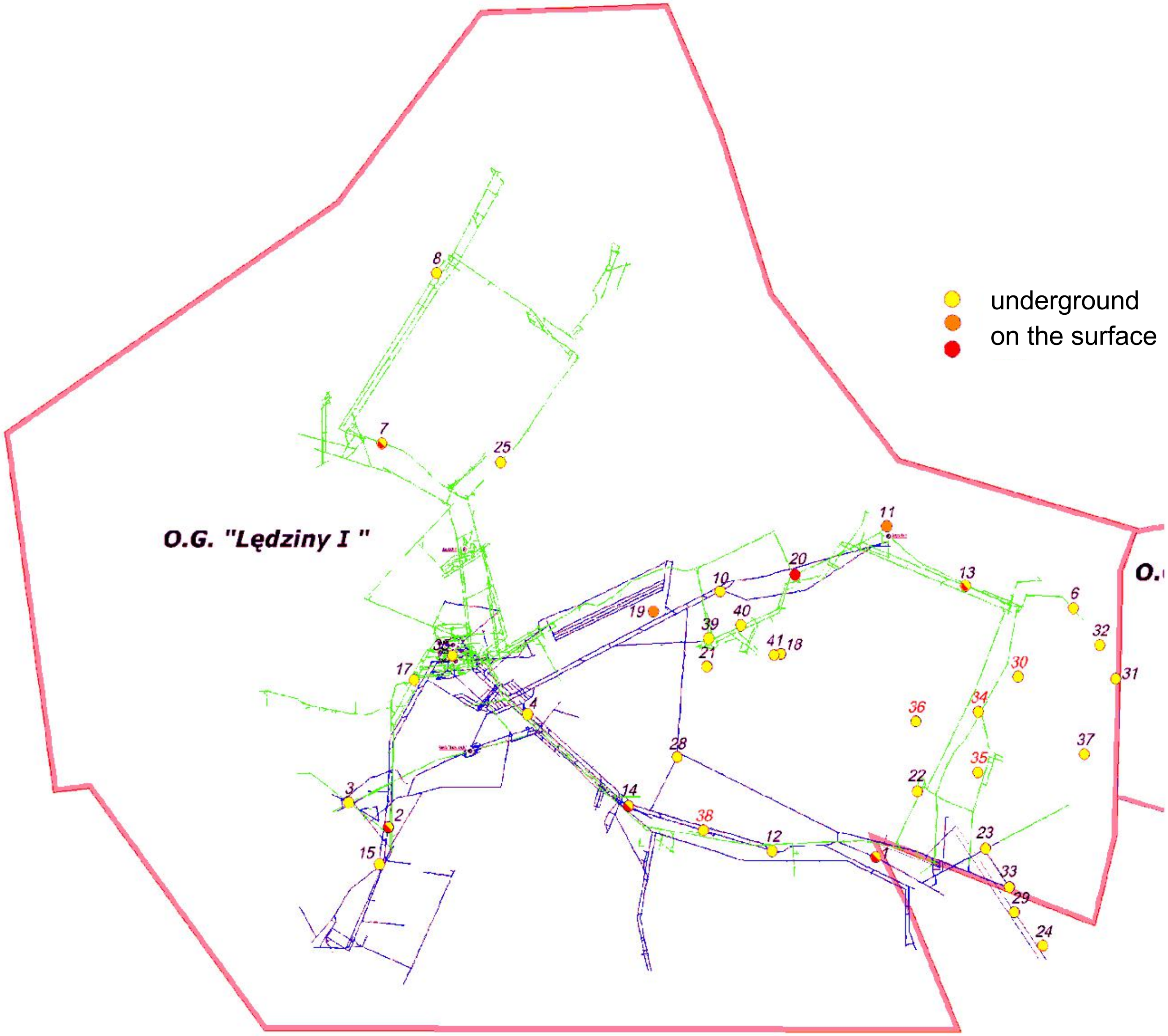
Prediction of ground particles velocity caused by mining seismisity on surface acc. GSI scale [m/s]



Prediction of ground particles acceleration caused by mining seismisity on surface acc. GSI scale [m/s²]

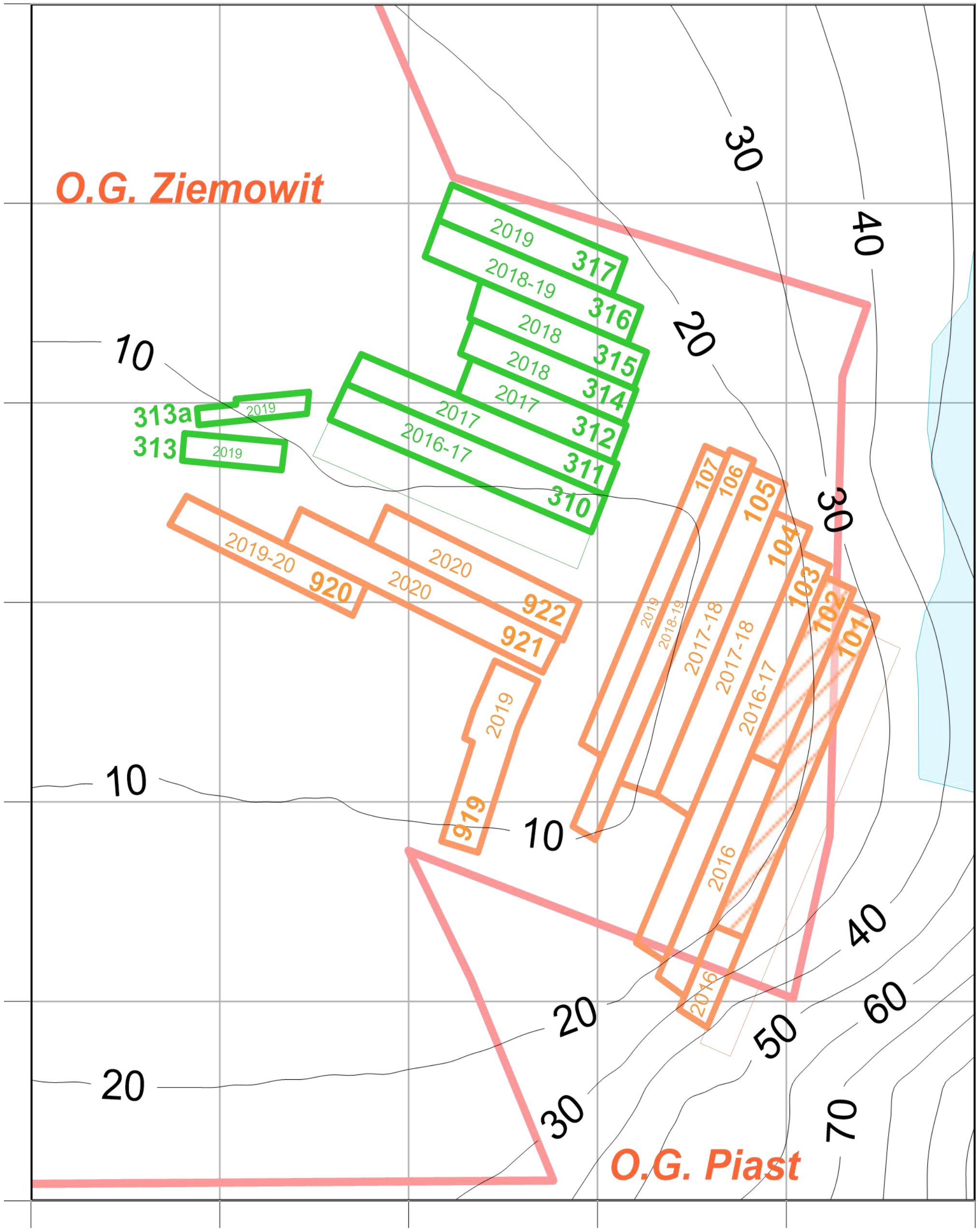


Seismicity measurement points layout - on the surface and underground - coal mine „Ziemowit”

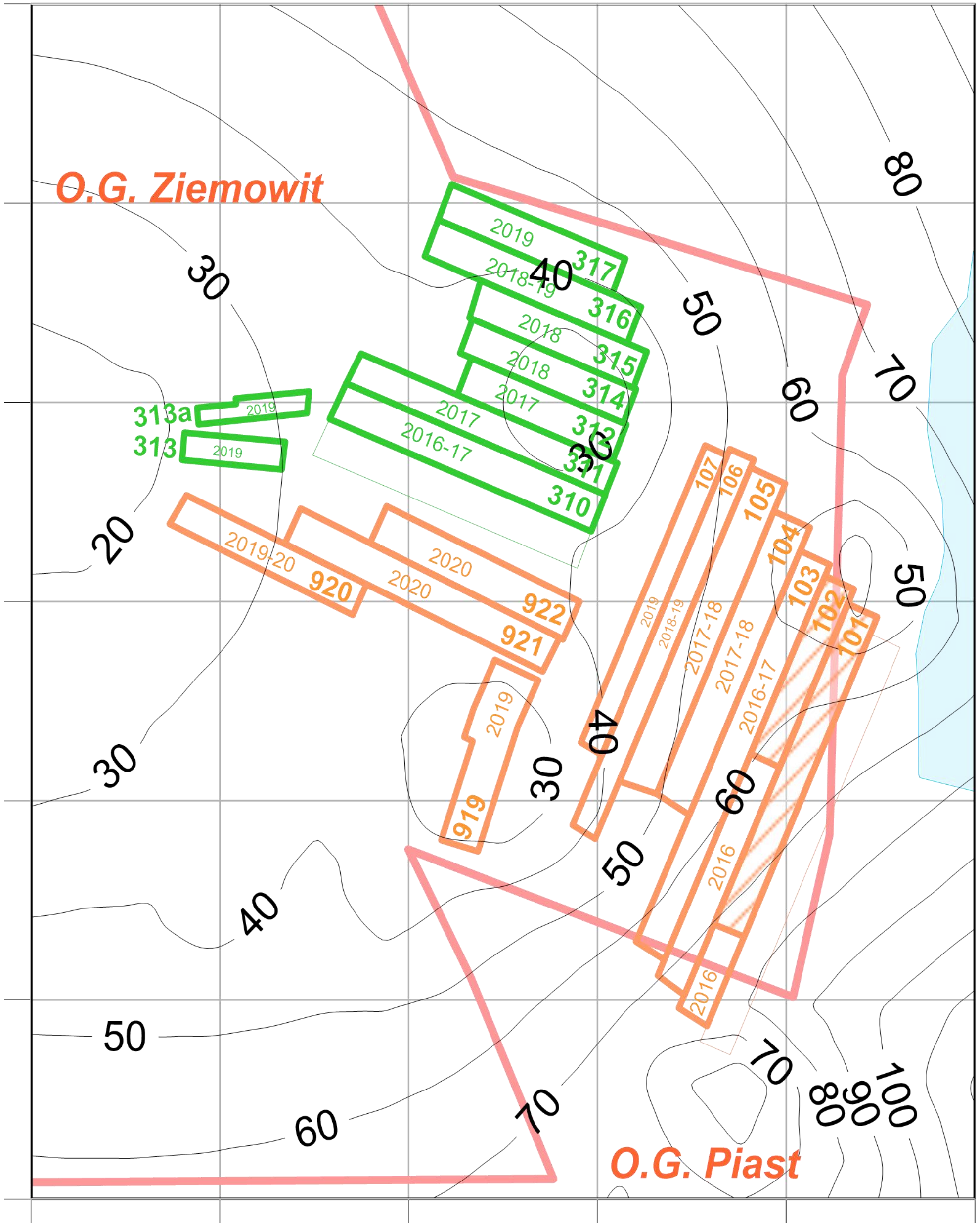


● underground
● on the surface
●

Average error of rockburst epicenter location



Average error of rockburst epicenter location



Rockbursts -
the serious problem,
the big challenge for mining engineers