Regularity of particle velocity decrease with scaled distance for rockbursts and shot holes

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The paper is intended as an analysis of particle velocity generated during rockbursts in deep coal mines in the Ostrava-Karviná Coal Basin (OKCB), which are recorded at five underground seismic stations. On the other hand, we realized field measurements in open-pit coal and shale mines in northwestern and central Bohemia in the course of blasting operations. Based on analysis of experimental data it was proved that the slope of straight regression lines n of peak ground motions for rockbursts varies between values of n = - 0.8 up to - 1.5, while n = - 1.8 up to - 2.5 were found for explosions in holes. While the monitoring system in the OKCB is in a continuous operation using three-component seismometers WDS-2, a massive seismometer VBP-3, which enables us to record ground motions in the near zone of the explosion, was occasionally used for experiments in open-pit mines.

***Key words**: rockburst, hole shot, particle velocity, scaled distance, cylindrical and spherical waveforms*

Introduction

Ground motions induced by rockbursts and/or by blasting operations may cause very often damage underground and on the surface of undermined area as well. Many field experiments proved the experience that damage to both underground workings and surface structures caused by these phenomena can be determined by means the only parameter, i.e. by particle velocity u_i, which seems to be the best criterion for damage estimation. Considering that our research was concerned with finding some relations between particle velocity u_i (m/s), distance d (m) and mass of explosives Q (kg) a new parameter had to be introduced, which enable us to substitute as distance, as the charge of explosion by one variable. This variable is denoted as scaled distance d^*, which is expressed by formula $d^* = d/\sqrt[m]{Q}$. In the case when we are dealing with rockbursts, a unit of energy E (J) is then applied instead of Q. Based on the literature review, e.g. Aldas, 2010; Arora and Dey, 2010; Egan et al., 2001; Hedley, 1990; Holub and Rušajová, 2011; Holub et al., 2011; Holub et al., 2011a; Mesec et al., 2010; Nateghi, 2012; Singh and Roy, 2010; Yugo and Shino, 2015; Zhao et al., 2014 it was documented that most of the authors generally quantities particle velocity and exponents m = ½ or m = ⅓ in formula for scaled distance used. While the decay for rockburst amplitude is characterized by the values n = - 0.8 up to -1.5, we obtained higher values for explosions, i.e. n = - 1.8 up to - 2.5. In principle the parameter n corresponds with geometrical spreading either of planar waveform according to the law $1/d$ (for rockburst), while for hole shots the waveform spreading in a spherical shape, which is close to the theoretical value $1/d^2$.

Particle velocity for deep level mines

As a consequence of geomechanical and geotechnical conditions and also anthropogenic activities in mines of the Ostrava-Karviná Coal Basin (Czech Republic), rockbursts have been recognized to be a serious seismic risk. Therefore, local as well as regional monitoring arrays were deployed there to investigate the actual seismic activity continually (Holub et al., 2013). In Fig. 1, the whole coalfield is displayed, which is divided into three partial basins, where the Ostrava and the Petřvald basins are closed now and as the only active remains partially the Karviná basin, because the Dukla Mine (1), the František Mine (6) and plant Barbora belonging to the Darkov Mine (5) (former the 1st May Mine) are closed now, and the Doubrava Mine (3) is also partially closed. Data from seismic stations situated underground, which are denoted by symbols A, C, D, K and M, were used for our analyses. They were used as a combination of three stations to monitor the induced seismic events, including rockbursts. The individual changing schedules of seismic stations are as follows: A+K+M, A+D+K and A+C+K. For this analysis, we used three-component records of 105 rockbursts which occurred during the interval 1993-2013. In the scope of geomechanical service of the Ostrava-Karviná mines, a rockburst is in general considered as a sudden failure of the coal seam and accompanying rocks into workings and roadways around. Simultaneously, much elastic energy accumulated in the coal seam and/or in the surrounding rock mass is released during this process of rock blocks destruction. In consequence of this physical phenomenon, the stricken workings are permanently destroyed regardless its energy so that they cannot fulfil

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their operational function. For general information, we have to stress that 40,000-50,000 induced seismic events are recorded in this coal field yearly, which represent the broad span of energies up to 10^8 J.

One of the essential parameters that were especially observed at the seismic stations situated *in-situ* were the
particle velocities of P- and S-waves. Previous experience obtained, e.g., by Holub et al., 2011, indicated that the best results for various relationships between the individual parameters related to the particle velocities of P- and S-waves could be reached by using the vectorial sum described by the following relation: $\sum u_{max} = [(u_i^Z)^2 + (u_i^{NS})^2 + (u_i^{EW})^2]^{1/2}$. Equations 1 and 2 were derived to determine the dependence of the particle velocity on the scaled distance for the vectorial sum of P- and S-waves data calculated for scaled distance $d^* = d/\sqrt{E}$.

P_{max}-waves u_{max} (m/s) = 1.06E-04 x $d^{*\,-0.899}$ $R^2 = 0.6995$ (1)
S_{max}-waves u_{max} (m/s) = 5.19E-04 x $d^{*\,-1.153}$ $R^2 = 0.8637$. (2)

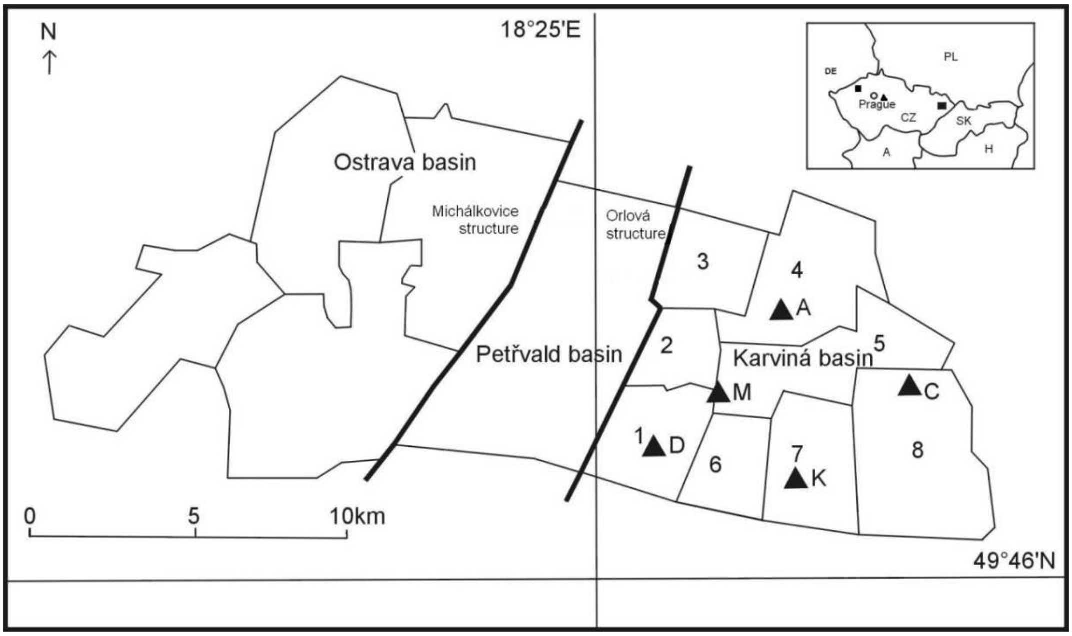

Fig. 1. The map of boundaries of coal basins (━) and demarcations of mines in the OKCB (─), 1 - # Dukla (closed), 2 - # Lazy, 3 - # Doubrava, 4 - # ČSA, 5 - # Darkov, 6 - # František (closed), 7 - # 9. květen and 8 - # ČSM (acc. to Dopita,1997), ▲ A, C, D, K and M represent positions of underground seismic stations. See miniature map situated in the upper right corner that documented: ■ locality of the Šverma Mine, ○ locality of the Filip Mine.

With respect to the fact that in previous papers, e.g., Holub et al., 2011, we presented only the final phase of solution, i.e. calculation of the vectorial sum regression of individual components of particle velocities. In this paper, we wanted to recognize and to show, how the individual components gradually contribute to the final waveform. For this reason all equations and the respective correlation coefficients R^2 for components of motion in directions NS (A), EW (B), Z (C) and their vectorial sum (D) are displayed separately, as shown, e.g., for P-waves in bilogarithmic scale are displayed for scaled distance $d^* = d/\sqrt[3]{E}$ in Fig. 2 and in Fig. 3 for S – waves. It was proved that the maximum scatter of particle velocities u_i (m.s^{-1}) of P- and S - waves was evident for both horizontal components that correspond to minimum values of correlation coefficients R^2. A little bit higher correlation coefficients were indicated for vertical components, and the best solution, i.e. minimum scatter of values u_i and maximal R^2 are guaranteed when the vectorial sum of individual components of particle velocities is applied. The explanation for the higher scatter values of particle velocities recorded by fixed oriented horizontal sensors is quite simple, because seismic rays are approaching from foci to the seismic stations from different azimuths.

Particle velocity for open-pit mines in northwestern Bohemia

Comparing the geological situation and method of mining in deep coal and open-pit mines exhibit distinct differences which are specific for both deposits: starting their position - Upper Silesian Coal Basin vs. brown coal near surface mines, different qualities of mined coal (hard vs. brown coal), age of deposit (Carboniferous vs. Neogene sediments), associated rocks to coal seams (hard vs. soft), depth of both deposits (deep vs. shallow) and their various physical and mechanical properties of the medium.

Experimental measurements were conducted at two localities of the Šverma Open-pit coal mine in the marginal area of the extensive mine, where mining activities were finished not so long ago. The experiments were aimed at investigations of open-pit face stability using blasting operations. The blast holes were drilled from the surface of stripping bank, and their depth varied approximately up to 20 m. The appropriate charges of explosives used had the *Q* values from 9 to 120 kg. The set of these experiments included one or 2-3 boreholes according to the mass of explosives Permonex V 19 determined for the hole shot.

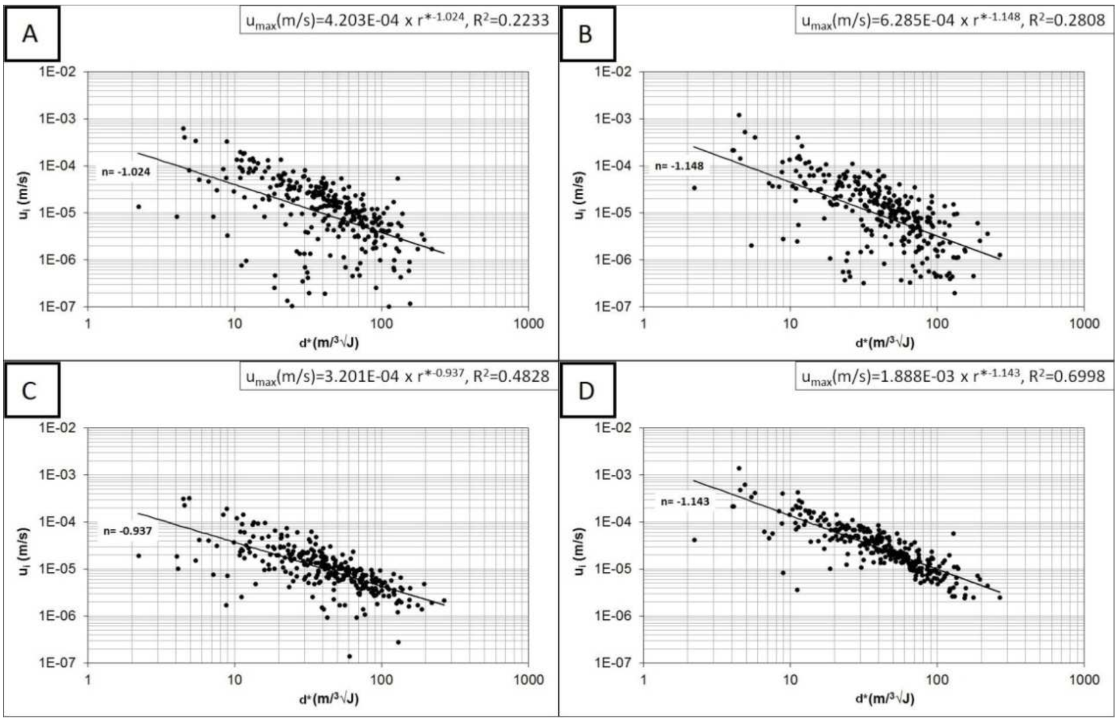

Fig. 2. The dependencies of particle velocity of P-waves log u_i vs. log scaled distance d and resulting approximation straight lines displaying in the bilogarithmic scale.*

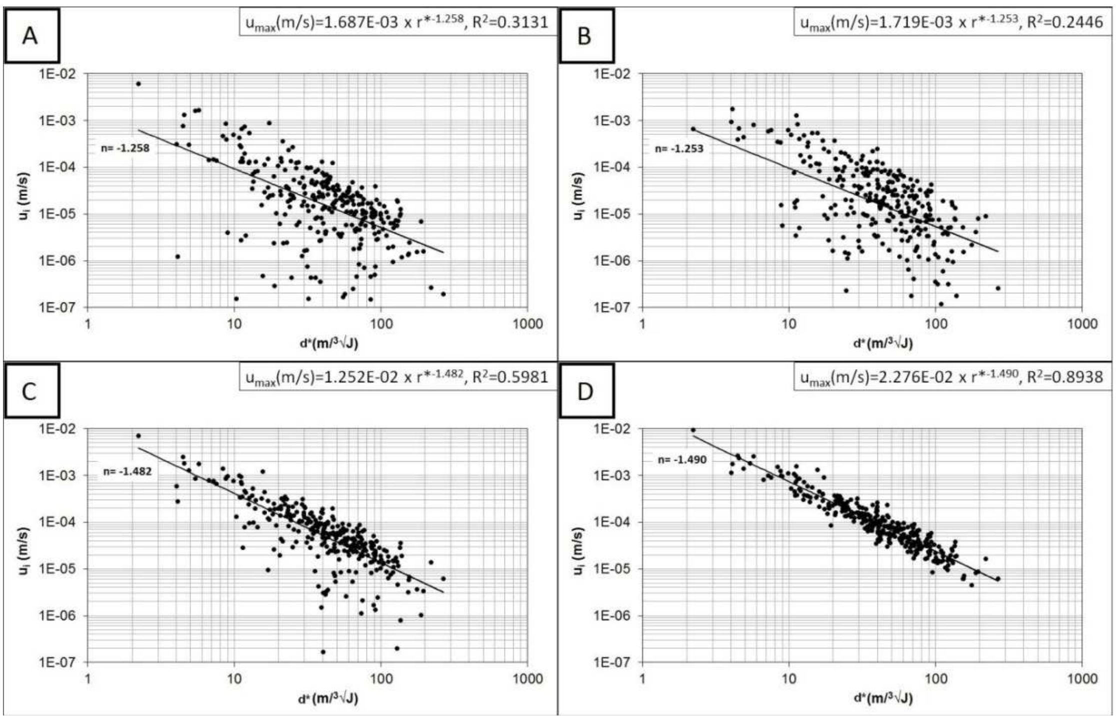

Fig. 3. The dependencies of particle velocity of S-waves log ui vs. log scaled distance d and resulting straight line approximations displaying in the bilogarithmic scale.*

Then these charges were tamped by sand up to the level of stripping bank and fired instantaneously. The massive sensor VBP-3 for recording of the radial component of ground motion (Rulev and Charin, 1961) was situated in the lowest part of the wall, where is acting in the near zone of the shock wave generated by the explosion (Fadeev, 1972). Simultaneously with the blasting, a gradual breaking of the wall was documented by the camera before and after each shot.

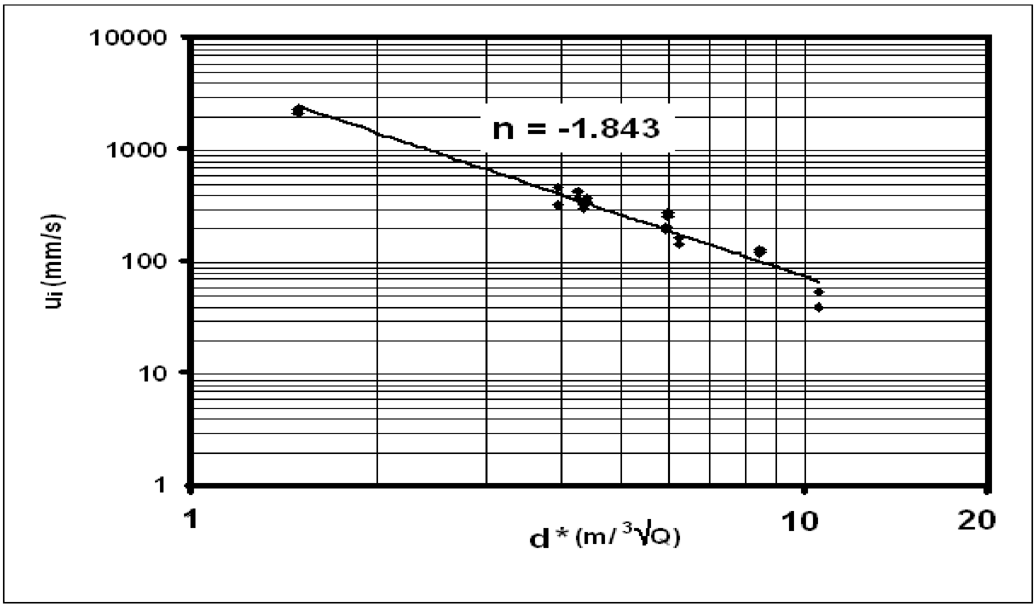

Fig. 4. The bilogarithmic graph of dependence log u_i vs. log d in the Šverma Open-pit Mine for the test site B.*

Two localities, where the seismic experiments were carried out, were chosen in the Šverma Open-pit mine. The first site (A) was situated in the area, where the massif was covered by overlying compact grey clays, the height of the wall was about 9-10 m. The second site (B) was situated roughly 20 m higher and the geological profile was rather complicated, because besides the layers of grey clays a part of the profile was represented by diagenetically little-consolidated sandstones and the lowest part of this profile was hidden by a talus fan of sandy material. Both sites are denoted in the miniature map in Fig. 1 by symbol ■. The interpreted data from the open-pit mine Šverma – site A and site B are characterized by the bilogarithmic graph of the dependence between log u_i vs. log d^* (Fig. 4). The straight regression lines for both sites are described by equations (3) and (4).

Test site A u_i (m/s) = 4.120 x $d^{*\,-1.894}$ $R^2 = 0.8612$ (3)

Test site B u_i (m/s) = 5.186 x $d^{*\,-1.843}$ $R^2 = 0.9519$. (4)

During the last explosion of Q = 120 kg, which was fired at the locality B, the massif was totally destroyed, and the seismograph VBP-3 was overwhelmed with a huge quantity of disrupted material. Afterwards, we had to wait almost one year for removal of this disrupted material, (Holub and Rušajová 2011).

Particle velocity for open-pit mine in central Bohemia

The Filip Open-pit Shale Mine is situated in Central Bohemia near Nové Strašecí, approximately 50 km northwestwards of Prague, its position denoted by ○ is displayed in Fig. 1 (see the miniature map). The mine is located at the southern margin of the Kladno-Rakovník Basin, where Upper Cretaceous rocks, lying subhorizontally, set on the Upper Carboniferous sediments transgressively. The sedimentary profile is represented by coarse-grained kaolinite sandstones, shales, conglomerates and, in the upper horizons, also some layers of celadon green were found. Seismic experiments were conducted in the central part of a deposit where Carboniferous shales almost crop out at the surface, being covered by a layer of sandy clay loam, the thickness of which varies from several metres.

The Filip Open-pit Mine u_i (m.s^{-1}) = 6.009 x $d^{*\,-2.256}$ $R^2 = 0.8935$ (5)

Based on seismic measurements carried out in the Filip Open-pit Shale Mine, we were able to determine the empirical dependence for radial component of particle velocity in the near zone of explosions Q = 10 - 50 kg fired in the respective shallower (5.5 up to 7 m) hole shots. Interesting results were also obtained owing to the application of special massive seismometers VBP-3 together with camera documentation.

Conclusions

Several findings can be pointed out:

- While the decay for rockburst particle velocity u_i is characterized by the values n = - 0.8 up to -1.5, we obtained higher values for explosions, i.e. n = - 1.8 up to - 2.5. In principle, the parameter n corresponds with geometrical spreading either of planar waveform according to the law *1/d* (for rockburst), while for hole shots the waveform spreads in a spherical shape, which is close to the theoretical value $1/d^2$.
- The peak particle velocities u_i observed in the Ostrava-Karviná Coal Basin at underground seismic stations yield values comparable with cited results of various authors, except for results from ultra-deep ore mines, e.g. in South Africa, where substantially higher values of particle velocities were recorded.
- The experiments in the open-pit mines proved that the results of observations are within the limits of observations of other researchers and, moreover, it was found that the photographic documentation of the progressive failure of the wall during blasting operations was a useful tool for more precise interpretation of observations.
- The application of the massive seismograph VBP-3 guaranteed reliable records of the stress wave in the near zone of the explosion.

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References

Aldas, G.G.: Explosive charge mass and peak particle velocity (PPV) - frequency relation in mining blast. *J. Geophys. Eng. 7, 2010, 223 - 231*.

Arora, S., Dey, K.: Estimation of near-field peak particle velocity - A mathematical model. *J. of Geol. Min. Res., vol. 2, no. 4, 2010, 68-73.*

Egan, J., Kermode, J., Skyrman, M., Turner, L.L.: Ground vibrations monitoring for construction blasting in urban areas. *Final Report, Caltrans, 2001, 1-11*.

Fadeev, A. V.: Disintergrating and seismic effect of quarry blasts. *Nedra, 1972, Moscow* .

Hedley, D. F. G.: Peak particle velocity for rockbursts in some Ontario mines. In: Rockbursts and Seismicity in Mines, *Fairhurst ed., Balkema A. A., Rotterdam, 1990, 345-348*.

Holub, K., Rušajová, J.: Peak particle velocity generated by rockbursts in underground coal mines and for shot-hole explosions in open-pit mines. *Acta Geod. Geophys. Hun., Vol. 46(1), 2011, 104-114; DOI: 10.1556/AGeod., 46.2011.1.9*.

Holub, K., Rušajová, J., Holečko, J.: Particle velocity generated by rockburst during exploitation of the longwall and its impact on the workings. Int. *J. Rock Mech. Min. Sci., Vol. 48, 2011, 92-949*.

Holub, K., Holečko, J., Rušajová, J., Dombková, A.: Long - term development of the seismic monitoring networks in the Ostrava-Karviná coal mine district. *Acta Geodyn. Geomater., Vol. 9, No. 2(166), 2013, 115-132*.

Ma, G., Hao, H., Zhou, Y.: Assessment of structure damage to blasting induced ground motions," *Engineering Structures, Vol. 22, 2000, 1378-1389*.

Mesec, J., Kovač, I. Soldo, B.: Estimation of particle velocity based on blast event measurements at different rock units. *Soil Dynamics and Earthq. Eng., vol. 30, no. 10, 2010, 1004-1009. DOI: 10.1016/j.soildyn.2010.04.011*.

Nateghi, R.: Evaluation of blast induced ground vibration for minimizing negative effects on surrounding Structures. *Soil Dynamics and Earthq. Eng., vol. 43, 2012, 133-138.*

Rulev, V. G., Charin, D. A.: Seismographs for large displacements recording. *Inst. Phys. Earth AS Sov. Union, Moscow, No. 16(183), 1961*

Sambuelli, L.: Theoretical derivation of a peak particle velocity-distance for the prediction of vibrations from blasting. *Rock Mech. Rock Eng , 2009: 547-56, doi:10.1007/s0063-008-0014-0.*

Singh, P. K., Roy, M. P.: Damage to surface structures due to blast vibration. *Int. J. Rock Mech. and Min. Sc. , vol. 47, no. 6, 2010, 949-961*.

Yugo, N., Shin, W.: Analysis of blasting damage in adjacent mining excavations. *J. of Rock Mech. and Geotech. Eng, 7, 2015, 282-290.*

Zhao, M., Huang, D., Cao, M., Chi, E., Liu, J., Kang, Q.: An Energy-Based Safety Evaluation Index of Blast Vibration. *Article ID 698193, 2014, Hindawi Publishing Corporation, 1- 8.*