Rock Burst Mechanics: Insight from Physical and Mathematical Modelling

J. Vacek, J. Vacek, J. Chocholoušová

Rock burst processes in mines are studied by many groups active in the field of geomechanics. Physical and mathematical modelling can be used to better understand the phenomena and mechanisms involved in the bursts. In the present paper we describe both physical and mathematical models of a rock burst occurring in a gallery of a coal mine.

For rock bursts (also called bumps) to occur, the rock has to possess certain particular rock burst properties leading to accumulation of energy and the potential to release this energy. Such materials may be brittle, or the rock burst may arise at the interfacial zones of two parts of the rock, which have principally different material properties (e.g. in the Příbram uranium mines).

The solution is based on experimental and mathematical modelling. These two methods have to allow the problem to be studied on the basis of three presumptions:

  the solution must be time dependent,
  the solution must allow the creation of cracks in the rock mass,
  the solution must allow an extrusion of rock into an open space (bump effect).

Keywords: rock burst, bump, mining, rock mechanics, mathematical and physical modelling.

1 Introduction

A rock burst is the most dangerous event that can occur during excavation works. Surrounding rock is extruded into an underground open space by a severe force during a rock burst. This event may cause an accident or even the death of mining workers, and it may destroy the excavation space. For this reason, studies of this problem are very important theoretically and for practical applications. See [1], [2], [3], and [7–9].

Sufficiently high pressure at the place of the rock burst is necessary for bump occurrence (usually great depth, but also tectonic pressure) and the rock must be brittle and must have a disposition for bumps (properties that allow the creation of bumps).

For the occurrence of bursts, mining velocity is also a very important factor. In the same conditions if we excavate slowly, we give the rock mass sufficient time to create cracks in the vicinity of the open space. For this reason, the stress concentration next to the excavation falls, and no bump occurs. If mining works proceed rapidly, cracks have no time to occur, and a rock burst appears. This feature is confirmed by old mining experience. For this reason, it is necessary to study this event as a time dependent problem.

Rock bursts were studied for the case of a mine gallery inside a horizontal coal seam. their mechanics and the stress distribution on the top of the seam were studied by mathematical and experimental modelling.

2 Experimental part

2.1 Testing devices

2.1.1 Loading cell

Fig. 1 shows loading cell. It consists of the lower steel tank, which is designed for the horizontal forces caused by the vertical load in araldite specimens. The loading cell is equipped with lucites on its sides, which allow observation of the samples during the tests. The tank is shown in Photo 2. This loading cell models (simulates) the rock mass in the vicinity of the seam. In the loading cell (with dimensions of 160/400/70 mm) we placed two araldite specimens, which model the coal seam.
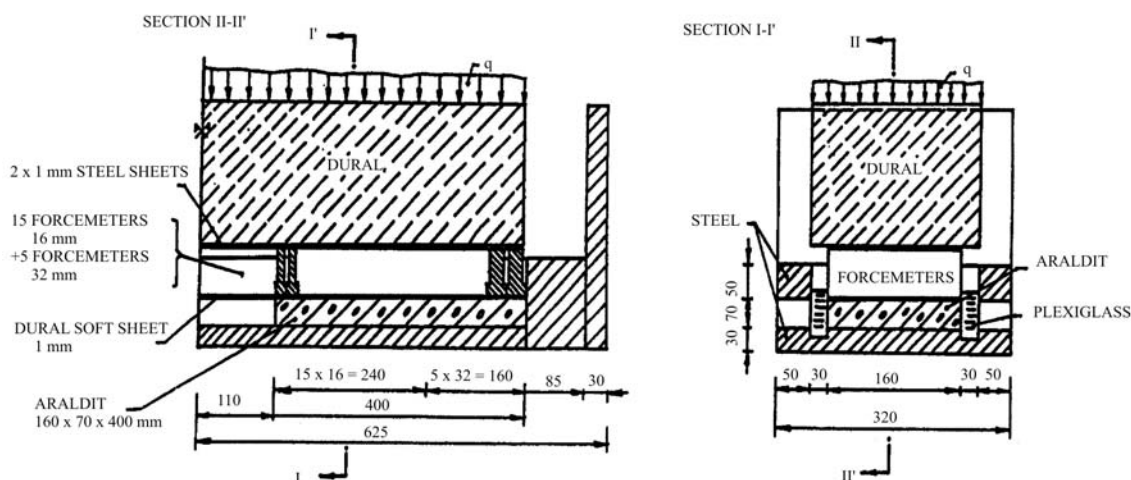

Fig. 1: Scheme of the loading cell

Photo 1: Testing device. Two camcorders recorded the test

Photo 2: Loading cell. Right with sample and force meters.

The gap between them corresponds to the width of a working gallery in a mine. We observed the mechanism and the history of coal rock bursts. The araldite specimen was covered with a soft duralumin sheet, and force meters were placed on it in the following manner: 5 comparatively thick force meters were placed near its outer edge, and another 15 thinner force meters were placed next to them (see Fig. 1 and Photo 2). In order to embed the force meters properly and to prevent them from tilting, another double steel sheet, 1 mm thick, was placed over the force meters. A block of duralumin 300 mm in height was placed over this sheet. This block simulates the handing wall and models the stress distribution similarly to that in reality (see Photo 1). The bedrock was modelled by a steel sheet.

2.1.2 Force meters

Photo 2 shows the force meters. The force meters are 160 mm in length, 68 mm in height, and 16 or 32 mm in width. There are 4 strain gauges on each force meter – 2 on one side, 30 mm from the edge of the force meter and 2 on the other side, 60 mm from the edge of the force meter. These allow us to measure the deformation along its full length.

The data from each force meter was read automatically every 10 seconds by a Brüel & Kjær strain gauge bridge, and deposited in a computer. It takes 1,2 s to read 40 force meters.
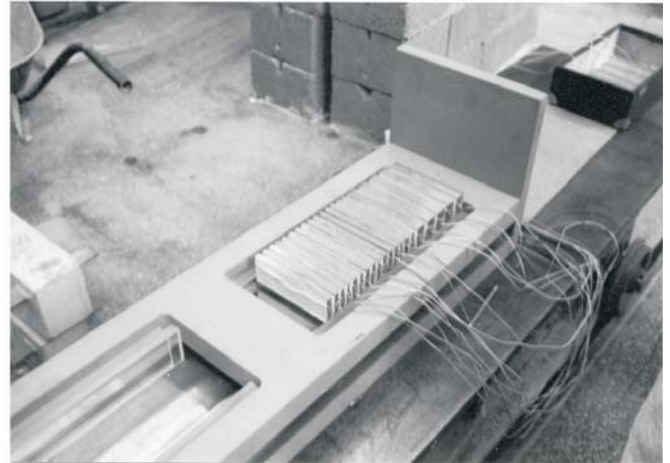
2. 1. 3 Conduct of the experiments

Three tests with various speeds of loading were used during our experiments. The whole system was uniformly loaded with a speed of loading of 50, 240 or 1200 kN/min. In all cases, the total force reached was 6 MN (the maximum force of the testing apparatus), i.e. the total experimental time was 5, 25 and 120 min, respectively. The average load of the araldite samples at the end of the test was 46.875 MPa, while the maximum load close to the mine gallery was approximately doubled, see Figures 2 and 3. The force meters can sustain this load without reaching the yield limit of their steel.

The reading frequency on the force meters was 10 s on a commercial Brüel & Kjaer bridge. The speed camera/camcorder was equipped with a 2 s loop tape, i.e. a recording was overwritten after 2 s. After the rock burst, the camera stopped and the last two seconds remained recorded.

The rock burst intensity was proportional to the intensity of the produced sound effect and, more accurately, proportional to the level of decrease in the load force. In the case of the strongest bursts, the force decreased all the way to zero.

2.2 Some of the results

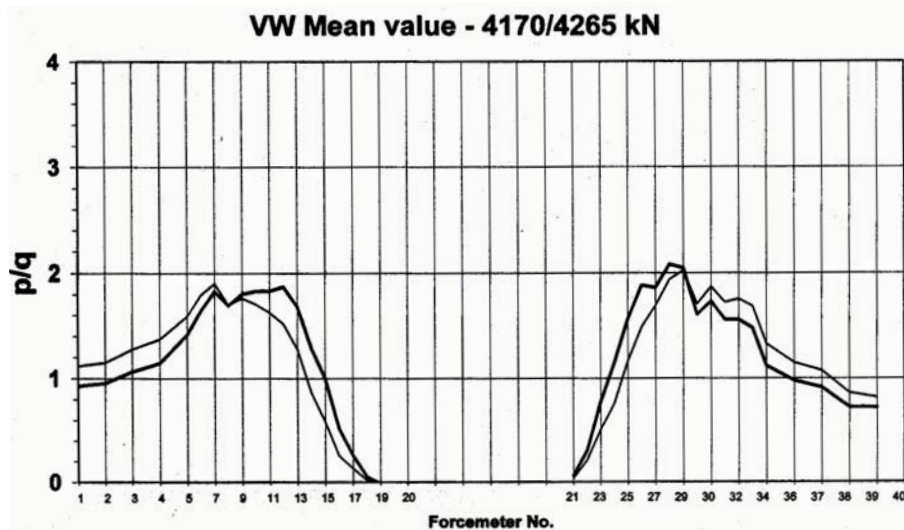More results are given in Ref. [4], [5] and [6].

Fig. 2: Mean stress distribution of the coal seam loading before (thick line) and after a bump. The force is 4170-4265.
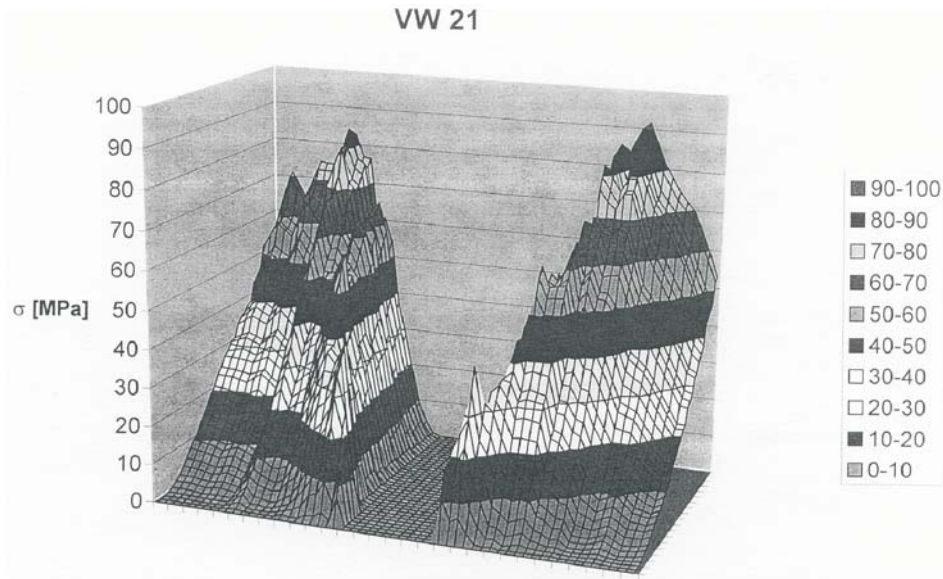
Fig. 3: Loading of the coal seam during test VW 21 in axonometry

Photo 3: State before bump

Photo 6: Late stage of bump

Photo 4: First extrusions appear

Photo 5: Early stage of bump

Photo 7: Bursting ($t = 0.060$ s)

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Photo 8: First wave of bump ($t = 0.146$ s)

Photo 9: Second wave of bump ($t = 0.178$ s)

2.2.1 Mechanics of bumps

The last part of the experiments were also recorded with a high-speed camera. This made it possible to watch the bumps as events lasting several seconds. Photos 3–6 were chosen from the continuous records. They show that the bump started (like an earthquake) with a small extrusion of rock mass, see Photo 3, followed by the main bump, Photo 4 and 5, and the state after the bump finished, Photo 6. The event sometimes ends with small extrusions of rock, thought not in the case described here.

2.2.2 What the tests showed

- The extruded rock mass is located on the only narrow strip next to the free rock surface. The breadth of this strip was only 15–40% of the height of the coal seam, and was proportionate to the bump force. The bigger the bump, the broader was the amount of extruded rock. The height of the coal seam was 70 mm in the experiment; the bump extruded approximately 10 to 30 mm of rock. After the bump, the surface of the coal was not smooth, it was uneven.

- In one case (out of about 30 cases) the bump came in two waves, see Photos 7–9.

- Bumps in experimental conditions last about 20 ms, (the two-wave bump lasted 50 ms), and whole events last about 0.5 s.

- The time, between the first extrusion and the bump was 20–200 ms.

- A great amount of energy is released during the bump. Part of it extrudes the rock mass to an open space, and re-action forces strike the rest of the rock. This creates new joints in the rock and the bump does not continue. When the bump is only weak, no joints appear in non-destroyed rock, and the second wave of bump comes, see Photos 7–9.

- The speed of the load considerably influences the rock burst intensity. While the intensity is rather low for the slow experiments, and the number of bursts is smaller (~3) and in the intermediate experiments the bursts are stronger and their number increases to about 5, for the fast experiments we also observe ~5 bursts, but of exceptionally high intensity. One of these bursts even damaged our experimental equipment – completely destroying the plexiglass sidings.

3 Mathematical model

PFC^{2D} (Particle Flow Code in Two Dimensions), developed by Itasca, USA, was used for the numerical modelling part of the project. A physical problem concerning the movement and interaction of circular particles may be modelled directly by PFC^{2D}. PFC^{2D} models the movement and interaction of circular particles by the Distinct Element Method (DEM), as described by Cundall and Strack (1979).

Particles of arbitrary shape can be created by bonding two or more particles together. These groups of particles act as autonomous objects, provided that their bond strength is high. As a limiting case, each particle may be bonded to its neighbour. The resulting assembly can be regarded as a "solid" that has elastic properties and is capable of "fracturing" when the bonds break in a progressive manner. PFC^{2D} contains extensive logic to facilitate the modelling of solids as close-packed assemblies of bonded particles; the solid may be homogeneous, or it may be divided into a number of discrete regions of blocks.

The calculation method is a time stepping, explicit scheme. Modelling with PFC^{2D} involves the execution of many thousands of time steps. At each step, Newton's second law (force = mass×acceleration) is integrated twice for each particle to provide updated velocities and new positions, given a set of contact forces acting on the particle. Based on

Table 1: Material properties of the coal, overburden and walls

Material	friction	kn	ks	density	n_bond	s_bond
coal	0.7	1e10	1e10	1900	1e4	1e4
joint planes	0.1	–	–	–	1e2	1e2
overburden	0.7	1e10	1e10	2300	2e5	2e5
walls	1.0	1e12	1e12	–	–	–

We used the following main material properties to get the required behavior:

- **friction** – friction coefficient of ball or wall surface (not friction angle)
- **kn** – normal stiffness of ball or wall when in contact with other balls [force/displacement]
- **ks** – shear stiffness of ball or wall when in contact with other balls [force/displacement]
- **density** – density of ball material [mass/volume]
- **s_bond** – shear contact bond strength [force]
- **n_bond** – normal contact bond strength [force]

these new particle positions, contact forces are derived from the relative displacements for pairs of particles: a linear or non-linear force/displacement law at the contacts may be used.

Model parameters: In order to model rock bursting in a coal mine gallery we created a 2D box in the computer and filled the upper part with larger overload particles (balls, 100 rows) and the lower part with smaller coal balls (50 rows).

The gallery was simulated by a rectangular opening in the lower part of the box (see Figs. 4–8). In the coal we set up joint planes at 45 degrees to horizontal. The material properties were set to model known coal mine data (cf. Table 1), with a time step of 0.00001 s. The loading was simulated by moving the top wall of the box downwards at a fixed speed at the beginning of the simulation (8000 steps). After the loading we typically performed about 200 000 integration steps (2 s) to
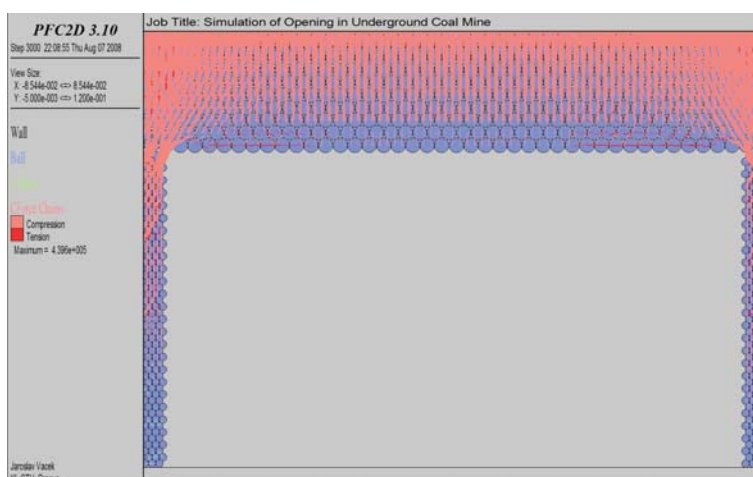

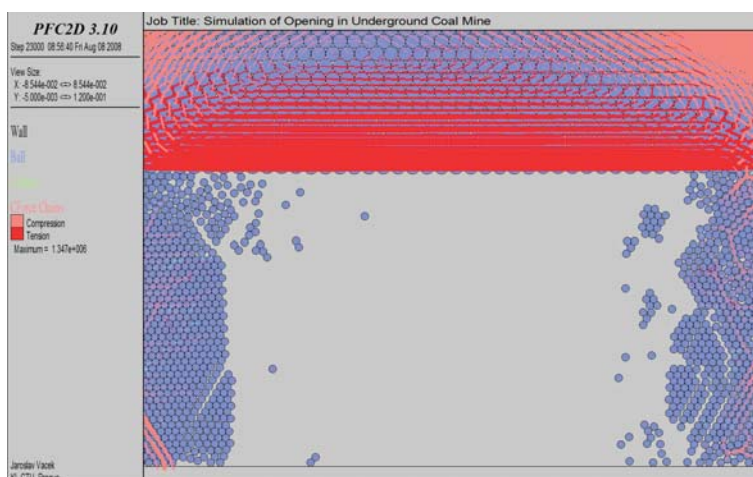Fig. 4: Mathematical model before the bump

Fig. 5: The first stage of the bump

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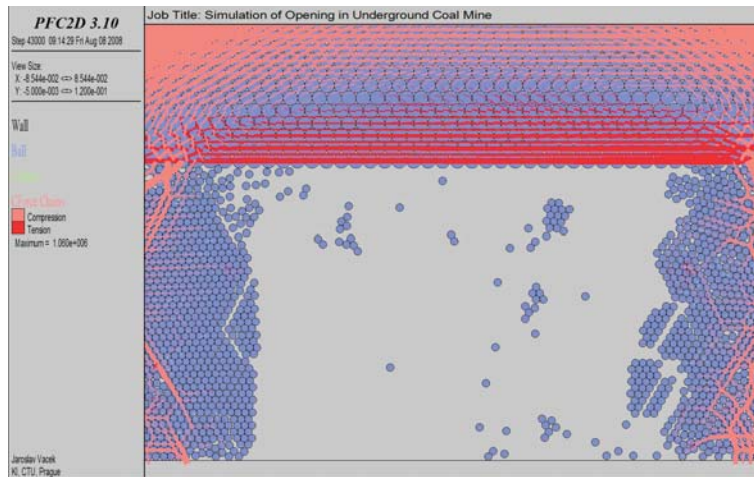
Fig. 6: Next stages of the bump

let the dynamics evolve. The bursting started rather early (0.1 s). Several simulations with varying numbers of coal particles and other parameters were performed with no significant impact on the qualitative results of the simulations.

Figs. 4–8 show details of the mathematical model of the bump, and Fig. 9 shows the typical stress distribution along the coal mine. The stress grows (I, II) until the first bump initiation (III). This occurs in the 5th measurement cycle approximately, then the stress decreases in this location, but it increases simultaneously in the 7th measurement cycle, when the second bump initiation occurs (IV). Subsequent bump initiations can be expected in the 8th and 10th measurement cycles (V, VI).

4 Conclusion

A combination of experimental and mathematical models appears very appropriate for a study of the stress distribution
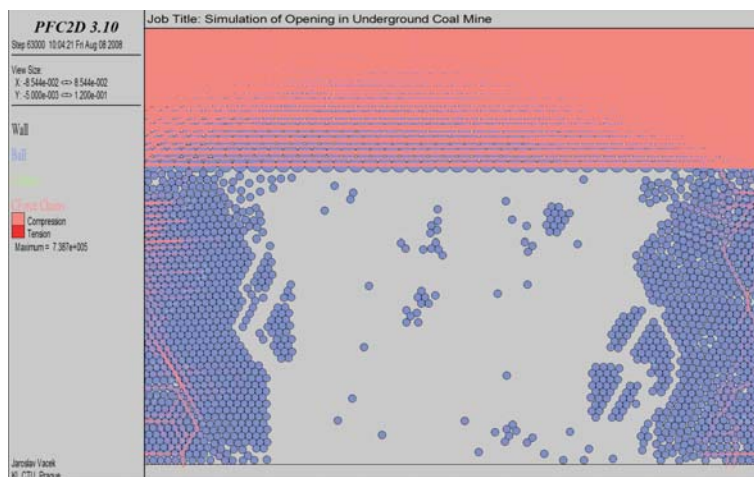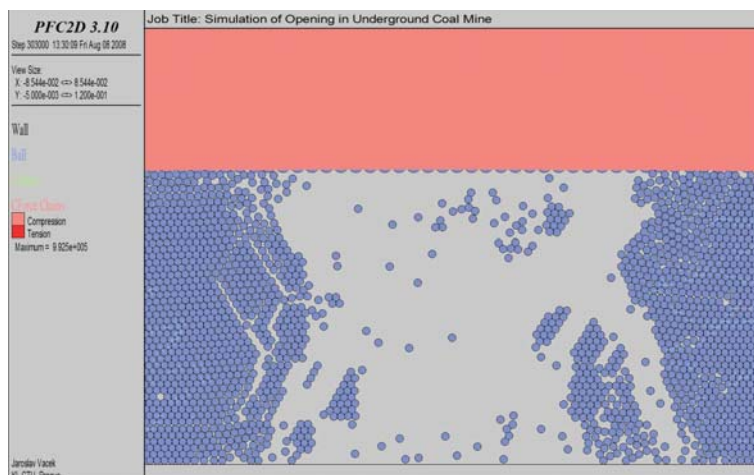

Fig. 7: Next stages of the bump
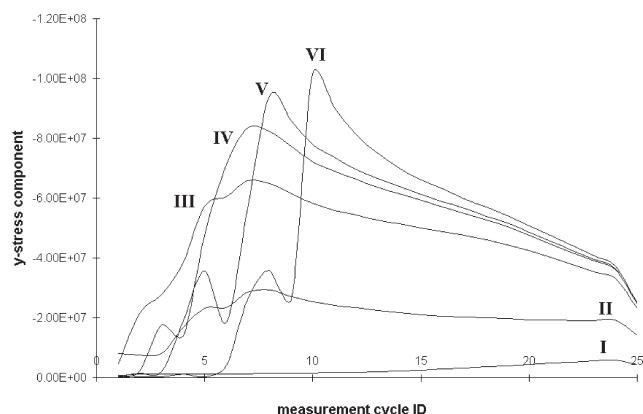

Fig. 8: Late stage of the bump

Fig. 9: Stress distribution along the coal seam
    I – 5000 cycles,
    II – 7000 cycles,
    III – 9000 cycles,
    IV – 12000 cycles,
    V – 15000 cycles,
    VI – 26000 cycles

in a coal seam before and after rock burst initiation. Both methods enable a time dependent study of the problem, and enable us to study the development of cracks during rock burst initiation, and then extrusion of material into an open space during a burst. Thus they offer a description of the problem that is very close to reality.

Acknowledgement

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Prof. Ing. Jaroslav Vacek, DrSc.
Phone: +420 224 353 549
e-mail: vacek@klok.cvut.cz

Czech Technical University in Prague
Klokner Institute
Šolínova 7
166 08 Prague 6, Czech Republic

RNDr. Jaroslav Vacek, Ph.D.
phone: +420 220 183 103
e-mail: vacek@eefus.colorado.edu

RNDr. Jana Choholoušová, Ph.D.
phone: +420 220 183 216
e-mail. jana@eefus.colorado.edu

Institute of Organic Chemistry and Biochemistry
Academy of Sciences of the Czech Republic
Flemingovo nám. 2
166 10 Prague 6, Czech Republic