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Rock bursts due to gas explosion in deep mines based on hexagonal and boundary elements

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ABSTRACT

The assessment of bumps occurrence in deep mines, which, for example, can occur during longwall mining, belongs to the most serious tasks for mining engineers since its consequences are commonly fatal. Aftermath of underground gas explosion on the bumps appearance at its early stage will be discussed. Discrete element method – hexagonal particles – is used in combination with boundary elements involving dynamical effects is the numerical tool for describing this phenomenon. Eigenparameters simulate the explosion. Some numerical examples show the ability of the method for applications to practice.

1. Introduction

A great attention of mining engineers is paid to a very dangerous phenomenon, which can occur during deep mining, and is known as rock burst or coal bumps. It causes disaster of such an extent that human lives are lost, material and energy expanses are enormous, and renovation of the afflicted mine is almost impossible. The grounds for bumps occurrence are various. Basically, accumulation of an extreme energy on the wall of the mine opening together with particular material conditions is mostly the reason. In former papers of the author, e.g., [1,2], the triggering conditions have been exclusively based on an assumption of nucleation of cracks in front of the mine face (side wall), and mutual material conditions were considered under which bumps take place.

It is worth noting that three phenomena can affect the stability of the side wall. The first is an explosion in the free space of the mine. Hence, a relatively complicated problem has to be solved, as the movement of a shock wave created due to a charge located inside of the mine is described by non-linear equations of gas dynamics (hydrodynamics), [3]. In the latter mentioned paper, a shock wave hits an arch structure, which behaves elastically. An influence matrix relating tractions (pressure) and displacements in the arch enables us to involve not only rigid structure, as is in most publications on this topic. A theoretical procedure is suggested in [4] to study the rock motion induced by explosion in an underground tunnel. Separately are solved pressures in the free space, which involve also the secondary wave surface or Raleigh wave, and the body motion. The effect of partially restricted wave generated by an explosion is discussed in [5]. Wide range of elements influencing the motion of the air and structure is taken into consideration, such as chemici and temperature effects, which accompany an explosion. Afterburning affect is also contemplated. Aftermath of an explosion inside of a closed space is concerned in [6], and the simulation of a terrorist attack using an explosive charge is studied. Programming package Autodyn is applied for computation, and the results are compared with extensive tests. The afterburning influence completes the study in terms of a residual gas pressure in a space with rigid boundaries. In all those cases mentioned in this paragraph, inertia forces basically influence the behavior of both the air and solid (structure, rock).

The second case, which may rule a possible bumps occurrence, is slow impact. Time dependent equations are solved, but the inertia forces are neglected. This is a case of hereditary problems of the rock surrounding the tunnel (mine). This is solved by the method, which is used also in this paper, in [7]. Also, the effect of an extreme change in temperature due to burning is dangerous as it may turn the original material properties, which are stable, to instare ones. Such a situation is studied in [8], for example.

Finally, preexisting displocations (cracks, fissures, and rifts) can be the reason for bumps triggering during the opening of underground spaces [9,10]. Moreover, the preexisting cracks may nucleate, grow, propagate, and lose stability in the rock mass, and also secondary cracks may be created. The stress concentration at the tips of the cracks is comparatively large, which may lead to the unstable growth of the cracks in fractured zones. In [10], the free hexagon method is applied.

Another one of typical reasons for bumps occurrence is that after adit is excavated, the distribution of vertical stresses changes

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from uniformly distributed in the virgin state to tortuous one with a peak above the coal seam. If coal burst occurs, the grains of coal are pushed out from the front part of the coal seam and are extruded to the free space of the adit created during the excavation. For example, if velocity of excavation is fast enough, the stresses in the rock and coal cannot reach sufficient redistribution, the concentration of stresses can exceed some admissible value and coal burst takes place. From experimental observations, natural conclusion follows the faster the velocity of mining the higher threat of bumps occurs. If the velocity of excavation is not considered, the problem of bumps occurrence is virtually stability problem, i.e., statical problem should be solved. If there is some necessity to take into account also dynamical effects, for instants, due to a fast excavation (appearing in the mathematical and numerical simulation by very fast developing Eshelby forces, [11]) or because of an aftermath of other resources of excitation (gas explosion, wave induced by other burst hitting the location of the trial adit), stability problem cannot be considered any longer and inertia forces must be involved into computation.

In case of describing dynamics of underground mass often, PFC (particle flow code), [12–14], is used, which has long lasting tradition and belong to the first types of discrete element methods (DEM). This method suffers from certain flaws: the continuum describing the rock mass is substituted by balls (disks in 2D), so that the stresses can be determined at the contact point between particles, and the real stresses are virtually impossible to establish. Although the behavior of particles after loss of stability is described in very illustrative way (this states are mostly out of interest to the designers, as once the bumps occur the movement of particles is so fast that in every case the aftermath of bumps is fatal), the bumps cannot be predicted with enough accuracy. Next, the material parameters are obtained from laboratory tests on samples simulating continuous medium, and identification of contact characteristics, [15], from the tests is almost impossible. Also, difference between virgin state before starting the mining and the state after excavation can hardly be described. Similar flaws occur in UDEC, a professional program from Itasca. Note that there are some interesting applications of PFC, such as an assessment of aftermath of earthquake on frame structures, piles, etc., where the material properties are transferred to springs, describing the material characteristics in PFC model; in this special cases, the spring stiffnesses can be identified in a better way. From these considerations, it generally follows that the prediction by the PFC has a very poor chance in planning the longwall mining.

Discrete element methods possess very important property: they turn the fracture mechanics problems into the contact problems, and the mechanical parameters can be identified in relatively accurate way. If classical numerical methods are applied to entire domain, it is necessary to employ certain approach from the field of fracture mechanics. Name here cohesive zone method, [16], for example, which employs Barenblatt's theory. In [17], simulation of rock cracking is based on homogenization of a representative volume element consisting from some phases such as stones, clay, and pores. Other methods can be used to solve the problem of nucleation of cracking. For example, name here Smooth particle hydrodynamics, [18,19], which is based on the partition of unity, and Manifold method, [20], which may involve both plastic behavior, e.g., [21], and damage, [22].

In order to feed numerical models with appropriate input data and to get knowledge about a reasonable approach for solving the problem, test experiments have been carried out. One of the possible experimental treatments was suggested in [23,24] where physically equivalent materials are employed. Conception of coupled modeling was suggested in [25], where rock bursts are studied in mines in extreme depth. The experimental models mostly start with similarity properties of the real material and the material of tested samples, [26,27]. Back analysis leading us to the identification of material properties of the material under consideration can then be realized using the trick published in [28,29]. The approach introduced there is based on a superposition of purely elastic strains and the eigenstrains (similarly elastic stresses and eigenstresses). Then, the eigenparameters may stand for plastic strains or relaxation stresses as free (design) parameters in appropriately selected optimization problem describing requirement that the computed and measured values of displacements, strains, and/or stresses are as close as possible at selected points (where the measured values can be obtained).

In [30–32], results from on site measurements are published, recommendations are provided on how to proceed in predicting the rock bursts and, which is of the most importance to us, the way of movement of freed elements is shown in these publications. Ground shocks in rock masses created by dynamic events such as rock bursts, coal bumps, or man-made or gas explosions are discussed in [33]. This article examines two aspects of the phenomenology: the propagation of the ground shock and its effect on underground structures.

The free hexagon method seems to be very promising, as the result from experiments and numerical models are in a reasonable compliance [1]. Similar model to the free hexagons is published in [34], where the behavior inside the particles is solved on the FEM basis. Necessary continuity of displacements suggested in [34] is fulfilled only at vertices of the hexagons, so that from mathematical point of view, this approach is at least suspicious. In the case of the firm bond between adjacent elements, the regularity is ensured in the case of free hexagons, which is not the case of the problem published in [34]. Note that the idea of hexagons probably stems from honeycomb model [35].

The latter requirement on continuity along the interfacial boundaries of adjacent element leads us to the idea of application of boundary elements [36], for example, which are used for describing the mechanical behavior inside the particles. It is well known that in this case, both interfacial displacements and tractions are of the same degree of approximations. One can use constant or linear distribution along the boundary of the elements, which in our case are identified by entire abscissas creating any particular hexagon (six boundary elements create each hexagonal element). The domain integrals to be created below can be calculated by the approach shown also in [11], for example.

In this work, interface section between static and dynamical states before and close after the bumps is characterized. The basic idea is very similar to PFC: pseudo-static states are considered, the mass is concentrated at the center of each particle, so that static states are solved separately by the BEM. Then, after such a simplification, the dynamic equations are written for particles, which are in a possible contact. The contact is described by Generalized Mohr–Coulomb law and identification of the way of contact is solved at each time step (statical state) using spring rules. The basic difference between the classical DEM, like PFC, consists in introducing correct definition of stress, as an area is taken into amount on the contact, while in the PFC, only contacts at points are enabled. First, the free hexagon method is described and basic formulas are derived, and then, some applications to rock bumps will be presented. Time dependent problem with the D'Alembert forces, which are caused by very fast movement of the particles, simplifies the body of the rock and coal seam to a set of hexagons, which are, or are not in a mutual contact. The material properties along the interfaces of adjacent hexagons are determined from the stress state, transformed to the contact tractions. The hexagons represent a possible shape of the grains (particles) the earth consists of. The most natural contact conditions obeying Generalized Mohr–Coulomb hypotheses may be simply introduced and, after imposing all such contact conditions, the localized damage, or