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Discrete element modeling of gravity flow of broken rocks in the technology of longwall top coal caving

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Abstract: The authors perform 3D discrete element modeling of pre-broken coal and dirt discharge in underground mining with sublevel caving of thick coal seams. The process of force interaction between rocks and powered roof support is analyzed. The difference between the discharge regimes with feeders equipped with smooth and corrugated surfaces is demonstrated. The mass flow of coal during discharge is shown.

1. Introduction

New technologies of thick gently and steeply dipping coal bed mining with the in-built effect of physical destruction are based on the use of rock pressure, which makes it possible to give extra options to mechanized mining equipment. As a consequence, new prospects open for development of technologies and structures of powered roof support. The scientific research and engineering evaluation of the technology of pre-broken top coal caving with the controlled discharge in mining thick coal seams are carried out in many countries [1–6]. The current-level study of mechanical means for longwall top coal caving in thick gently and steeply dipping coal beds shows that the improvement of the related technologies and powered roof supports consists in the search and implementation of new engineering solutions on discharged coal flow regulation. These technologies are united by the common idea of controlling coal flow to face conveyor using feeders installed in the powered roof support units. For the implementation of such technologies, the optimal directions of top coal treatment to ensure the wanted coal flow mode have earlier been substantiated: vibroseism treatment and hydraulic fracturing of coal seams using wells drilled from intermediate or sublevel drifts.

Previously proposed configuration of powered roof support with adjustable coal flow to face conveyor is developed with regard to geomechanical processes in coal and roof rocks, includes benefits of the known alternatives and eliminates their shortcomings (figure 1) [7, 8].

Introduction of feeders in the structure of powered roof support for discharge and load of caved top coal is a new trend in high-productive technologies in coal mining. Thus, the studies into the basic relations and mechanisms that govern rational designs of powered roof support with the forced-and-adjustable coal discharge are of the fundamental and applied relevance.

This paper describes the numerical experiment results on simulation of gravity flow of pre-broken rock mass aimed to find regular patterns in interaction between powered roof support and granular material in the course of discharge.
The most promising method to model deformation of geomaterials is the discrete element method DEM [9]. Efficiency of this method is connected with the focusing of the modern geomechanical research on the role of the internal structure of a medium. Granular materials possess such fundamental properties as dilatancy, internal friction and cohesion, which result in the nonlinear behavior and anisotropy. Within DEM a study domain is modeled by a set of discrete elements (particles) having spherical shape, as a rule. Particles are assumed non-deformable, and the rate of their deformation is represented by a value of their overlap. Movement of particles in space is described using Newton’s law of motion. Forces arising on collision of particles are calculated from models of the contact mechanics with regard to the normal and tangential components. In the framework of such approach with selected particle interaction potential, it is possible to describe movement of solid particles in fluid, heat exchange processes, adhesion, polydisperse media, etc. [10–13].

2. Discrete element modeling

In accordance with DEM, a granular material is represented by a set of $N$ spherical particles (discrete elements). Each $i$-th element has a radius $r_i$, the known physical properties of density, elasticity and plasticity moduli, and contact properties of friction, cohesion, etc. ($i = 1, \ldots, N$). Movement of each $i$-th discrete element with the gravity center radius $x_i$ consists of translational and rotation motions and is given by:

$$m_i \frac{d^2 x_i}{dt^2} = \sum_j f_{ij} + m_i \mathbf{g}$$

(1)

$$I_i \frac{d^2 \theta_i}{dt^2} = \sum_j (r_{ii} \times f_{ij} + M_{rij})$$

(2)

where $\theta_i$ is the rotation of an $i$-th particle relative to coordinate axes; $m_i$ is the mass; $I_i$ is the moment of inertia; $\mathbf{g}$ is the acceleration of gravity; $r_{ii}$ is the vector from the particle center to a contact point. The contact force $f_{ij}$ affects the $i$-th particle from the side (or boundary) of a $j$-th particle, and depends on the overlap of the particles, as well as on the elasticity and plasticity moduli; $M_{rij}$ is the moment of rolling resistance of particles. Summing in (1) and (2) is carried out over all elements and boundaries which contact the $i$-th particle. As the shape of discrete elements is assumed unaltered over the time of contact, the rate of deformation is described by the value of overlap of the contacting particles.
The force interaction at the contact point between the spherical particles \(i\) and \(j\) is presented in the vector form based on the Kelvin–Voigt viscoelastic model with regard to the normal and tangential components (figure 2):

\[
f_{ij} = f_{n,ij} n_{ij} + f_{t,ij} t_{ij}
\]  

(3)

Here, \(f_{n,ij}\) and \(f_{t,ij}\) are the viscoelastic normal and tangential components of the contact force, respectively; \(n_{ij}\) is the unit vector governing the plane of contact between two spheres (vector of normal to the intersection plant of spheres, directed along the line connecting the centers of the spheres); \(t_{ij}\) is the unit vector belonging to the contact plane.

![Figure 2. Schematic of the contact interaction of spherical particles based on the Kelvin–Voigt rheological model.](image)

It is chosen to determine the normal and tangential forces in (3) in terms of particle interaction based on the Hertz law and from the Mindlin–Deresvich scheme, respectively [14–16]. As the normal and tangential components of the contact force have been determined at each contact, we go to the next step of loading, and the calculations are repeated for the existing and new contacts.

Making an original equilibrium packing of solid spherical particles is an important initial step in discrete element modeling and is studied as a separate problem by many authors [17–19]. Currently, a number of approaches to generation of an original dense packing are available and differ by the way of achieving the final configuration of the domain composed of separate particles. In this paper, we use a dynamic scheme of simulation of particle motion under the action of a preset external force (gravity). Here, a set of initially noncontacting particles of preset size move under gravity in an assigned bounded domain, and the final equilibrium state is determined with regard to the particle–particle and particle–boundary contact interactions.

3. Numerical experiment

The 3D modeling of powered roof support unit (figure 3) is carried out using the widely applicable STL File Format (StereoLithography). In this format, information about an object is stored as a list of triangular faces which describe the object surface and the normal to the faces. Such representation only shows the geometry of the object surface without its color, texture or other model attributes included in the automated design systems.

The numerical calculations disregard the force interaction between the elements of powered roof support (when they contact or intersect). The forces between particles and powered roof support are calculated from formula (3).
Let us discuss 3D problem formulation. Let in the space Oxyz a domain (container for granular material) be set as a parallelepiped bounded by planes oriented along the coordinate axes; the upper boundary is free of stresses (figure 4). The container has a length of 10 m and a width of 2 m; the material fill height is 12.5 m. The vector of gravity \( \mathbf{g} = (0; 0; -9.81) \) is directed along the axis \( Oz \) vertically downward. The front and back walls are perfectly smooth, i.e., the condition close to plane deformation state in the \( Oy \)-direction is fulfilled. The physical parameters of particles conform with the properties of coal (table 1). The coal seam thickness is assumed as 3 m, the height of the powered roof support unit is 3.5 m.

![Figure 3. 3D model of powered roof support with discharge (a), (b); equilibrium state of material when the feeder is switched off (c).](image)

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|                  | Coal     | Dirt    |
|------------------|----------|---------|
| Elasticity modulus, MPa | 5.4\times10^4 | 1.5\times10^4 |
| Poisson's ratio  | 0.16     | 0.21    |
| Density, kg/m³   | 1350     | 2500    |
| Diameter, m      | 0.08–0.16| 0.08–0.16|

Figure 4 shows such elements of powered roof support as canopy 1 with a length of 2.5 m, vertical flow shield 2 with a height of 1.75 m to limit velocity and volume of granular material flow; feeder 2 with a length of 3.575 m arranged at an angle of 12° relative to a horizontal plane; discharge 4 with a width of 1 m (initially closed); side guards 5 with a spacing of 1 m.

After creation of equilibrium packing, granular material was represented by a set of 127 000 discrete elements composed of 58 t of coal particles and 195 t of dirt particles. Then, the sliding friction angle \( \varphi_i = 30^\circ \) and the rolling resistance angle \( \psi_i = 30^\circ \) between particles were fixed. For the visualization of the discharge kinematics, discrete elements were colored. In the course of discharge, particles with the gravity center coordinate meeting condition that \( z_i < 0 \) were removed. Thus, bulk flow of coal and dirt was calculated.

The scope of the numerical experiment embraced simulation of broken rock flow by gravity. In this case, the shield limiting flow rate and volume was withdrawn and the feeder was inoperative. Figure 5 shows the deformation patterns of coal and dirt flow by gravity at certain moments of time. It is seen that without the limitation of the flow velocity and volume from the side of the powered roof support, the particles of dirt, which have higher density than the particles of coal, enter the flow and cause dilution and high loss of the valuable component.
Figure 4. Schematic of numerical experiment on coal discharge.

Figure 5. Stages of coal discharge at certain times, s: t = 3.6 s (a); 7.2 (b); 10.8 (b); 14.4 (b); 18.0 (b); 21.6 (f).
The mentioned fact is confirmed by the plots of the bulk flows of coal $M_c$ and dirt rock $M_r$ in figure 6. The bulk flow is found as the total mass of certain material particles passing the plane $z = 0$ per unit time.

![Figure 6. Bulk flows of coal (●) and dirt (▲) in the course of discharge.](image)

The process of elliptical flow zone formation [20] above the discharge is illustrated in figure 7. Here, the kinematic patterns of discharge at fixed times, namely, distributions of moduli $|v_i|$ of velocity vectors of each particle, are colored. The dark shade are the particles with low velocity (close to zero), the light shade are the particles with high velocity (to 5 m/s). It is evident in figures 5 and 7 that the discharge configuration appears above the outlet and propagates up to the free surface.

![Figure 7. Distribution of velocity vector moduli of each particle at fixed times, s: $t = 3.6$ (a); 7.2 (b); 10.8 (c); 14.4 (d); 18.0 (e); 21.6 (f).](images)
Two experiments were meant to analyze influence of the feeder structure on the discharge flow behavior. To this effect, the feeder surface was set smooth in the first experiment and as corrugation in the form of steps 0.15 m long and parallel to a horizontal plane. The feeder tilt was 12° in both experiments. The 3D model of the powered roof support with the corrugated feeder is demonstrated in figure 3c. As soon as broken rock mass reaches equilibrium state, the discharge was opened and the material flew until the next stage of equilibrium state. Such state is provided by the immobile vertical shield during deactivation of the feeder. In the experiments, the pressures on the shield and the feeder, \( P_d \) and \( P_f \), were recorded (figure 8).

Later on, the feeder was set into back-and-forth motion by the law:

\[
X_f = A(1 - \cos \omega t)
\]

where \( X_f = (x_f, y_f, z_f) \) is the radius-vector of the feeder center of gravity; \( A = -0.15(\cos 12^\circ; 0; \sin 12^\circ) \) is the amplitude of vibrations; \( \omega = 0.5 \) is the frequency of vibrations. In this manner, the total travel of the feeder is 0.3 m and its vibration period is 2 s.

Owing to contact friction between the particles and feeder, the material was involved into motion. In some time, the flow gained steady state. The coal bulk flow rate \( M_c \) in the described mode of discharge is shown in figure 9. In case of the smooth feeder, average \( M_c \) is 47 kg/s at the total discharge mass of 2193 kg of coal (figure 9a). With the corrugated feeder, these indexes are 32 kg/s and 1500 kg, respectively, which is an unexpected and surprising result (figure 9b).
Unlike in situ tests, the numerical experiment readily allows recording forces applied by the granular material on the powered roof support elements. The force interaction between the flow and the powered roof support is described in figure 10. The variation in the pressure $P_d$ (kPa) on the immobile vertical shield in case of the smooth and corrugated feeders is shown in figures 10a and 10b, respectively. It is seen that the change in the pressure of the granular material flow has periodic behavior and reaches extremums at the points of the end positions of the feeder. The peak pressure on the shield is higher in case of the corrugated feeder. The horizontal component (figures 10c and 10d) and vertical component (figures 10e and 10f) of the total force exerted by the flow on the feeder changes periodically, as well. It is worthy of noticing that the peak vertical load on the smooth feeder is higher by an order of magnitude as against the corrugated feeder.

![Figure 10](image-url)

**Figure 10.** Pressure of broken rocks on the shield (a, b); horizontal (c, d) and vertical (e, f) components of the total force on the smooth and corrugated feeder, respectively.
4. Conclusions
The described discrete element model of gravity flow of broken rocks in the technology of longwall top coal caving includes all basic process stages: creation of initial equilibrium state of rocks; discharge of the flow to the feeder of powered roof support; functioning of the feeder and further discharge in accordance with the flow chart of the powered roof support operation.

The study demonstrates periodic nature of variation in the material bulk flow rate and in the pressure exerted by the flow on the elements of the powered roof support in the course of discharge. The influence of the feeder surface configuration on the study characteristics is illustrated.

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References
[1] Melnik V V and Suschchev R A 2009 Mining Informational and Analytical Bulletin 5 198–210
[2] Jabinpoua A, Bafghib A Y and Gholamnejad J 2016 International Academic Journal of Science and Engineering 3(2) 102–109
[3] Kumar R, Singh A K, Mishra A K and Singh R 2015 International Journal of Mining Science and Technology 25(6) 885–896
[4] Hebblewhite B K 2005 The 19th International Mining Congress and Fair of Turkey IMCET2005 (Izmir, Turkey) pp 169–178
[5] Guo J, Ma L, Wang Ye and Wang F 2017 Energies 10 (9) 1371
[6] Unver B and Yasilili N E 2006 International Journal of Coal Geology 66(4) 227–252
[7] Klishin V I, Shundulidi I A., Ermakov A Yu and Soloviev A S 2013 Technology of Excavation of Reserves of Thick Flat Seams With the Release of Coal (Novosibirsk: Nauka) p 248
[8] Klishin V I, Fokin Yu S, Kokoulin D I and Kubanychbek B. Thick Coal Mining With Powered Support with Adjustable Coal Discharge 2007 (Novosibirsk: Nauka).
[9] Cundall P A and Strack O D L 1979 Géotechnique 29(1) 47–65
[10] Lavrikov S V and Revuzhenko A F 2016 Journal of Mining Science 52(4) 632–637
[11] Klishin S V, Lavrikov S V, Mikenina O A and Revuzhenko A F 2018 Journal of Physics: Conference Series 973(1) 012008
[12] Klishin S V, Lavrikov S V and Revuzhenko A F 2017 AIP Conference Proceedings 1909 020086
[13] Lavrikov S V and Revuzhenko A F 2017 AIP Conference Proceedings 1893 030122
[14] Johnson K L 1985 Contact Mechanics (Cambridge University Press)
[15] Mindlin R D 1949 J. Appl. Mech. 16 259–268
[16] Mindlin R D and Deresiewicz H 1953 J. Appl. Mech. (20) 327–344
[17] Guises R, Xiang J, Latham J-P and Munjiza A 2009 Granular Matter 11(5) 281–292
[18] Makse H A, Johnson D L and Schwartz L M 2000 Physical Review Letters 84 4160–4163
[19] Revuzhenko A F, Klishin S V and Mikenina O A 2015 Physical Mesomechanics 18(3) 244–249
[20] Hustrulid W and Kvapil R 2008 5th International Conference and Exhibition on Mass Mining (Luleå Sweden) pp 107–132