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MODELING AND SIMULATION OF COAL LOADING BY CUTTING DRUM IN FLAT SEAMS

MODELOWANIE I SYMULACJA ŁADOWANIA WĘGLA PRZEZ ŚLIMAKOWY ORGAN URABIAJĄCY W NISKICH POKŁADACH

This paper presents a methodology for modeling work of a coal shearer work in low longwall coal seams where the wall height does not exceed 1.5 m. In such conditions, an important issue is the process of loading the ore from shearer cutting drum on an armored face conveyor and selection of appropriate kinematic parameters to avoid choking. Discrete element method was used to model coal seam. This method allows for efficient simulation of physical systems composed of many separate components. Methods and algorithms based on existing theoretical models were developed to imitate coal cutting process. Main focus of analysis was put on coal stream movement for different variants of the shearer construction and kinematic parameters.

Keywords: discrete element method, longwall mining, shearer, armored face conveyor

W artykule przedstawiono metodykę modelowania pracy kombajnu ścianowego w niskich pokładach węglowych, w których wysokość ściany nie przekracza 1,5 m. W takich warunkach, istotnym problemem jest proces ładowania urobku na współpracujący z kombajnem przenośnik zgrzebłowy i dobór parametrów kinematycznych tak, aby nie doszło do zadławienia się organu. Ma to szczególne znaczenie w wyrobiskach niskich gdzie tak zwana furta ładowania jest wymiarowo/gabarytowo ograniczona. Do zamodelowania calizny wykorzystana została metoda elementów dyskretnych, pozwalająca na efektywne odzwierciedlenie układów fizycznych składających się z wielu odrębnych elementów. Opracowano metody i algorytmy pozwalające na imitację urabiania w oparciu o istniejące modele teoretyczne a główny nacisk położono na analizę ruchu strugi odspojonego urobku dla różnych wariantów pracy kombajnu i parametrów kinematycznych.

Słowa kluczowe: metoda elementów dyskretnych, system ścianowy, kombajn, przenośnik zgrzebłowy

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1. Introduction

New technologies and design solutions of mining machines allows for the exploitation of coal in more and more difficult geological conditions. In the case of flat beds, correct assessment of the loading process by the shearer drum is very important because of the much greater probability of choking. Limitations in the mining area resulting from the wall geometry, shearer dimensions or armored face conveyor bends cause a reduction of the so-called loading gate. Loading gate in this case is the minimum cross section that excavated material stream must overcome, limited by the shearer arm and the profile of the conveyor panline (Fig. 1). Such defined loading gate has a variable cross-section in the process of cutting, depending on the position of the arm and work direction of the shearer. Extreme loading conditions occur when the cutting drum is working at the height of the conveyor panline.

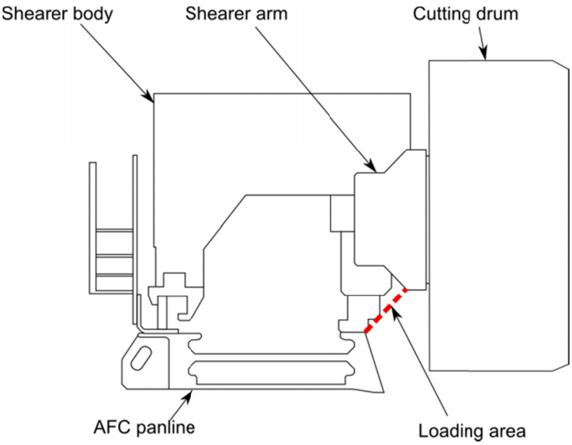


Fig. 1. Height of a material loading area

In such conditions a correct esteem of the material output from shearer onto the armored face conveyor and the nature of material stream is of upmost importance. It can prevent or minimize some potential problems of cooperation of these machines.

Commonly used analytical methods treat loosened, crushed output based on the theories of the continuous deformable bodies. Despite the inclusion of some specific effects using the experimentally determined correction factors, such an approach does not allow for the reproduction of the real mechanics of the material and leads to a significant simplification of the issues discussed. Their use is therefore limited to simple cases so alternative methods might be of interest – laboratory based (Wydro & Krauze, 2011) or numerical computations.

Today's computational capabilities of modern computers and numerical methods dedicated to solving problems related to the mechanics of particulate materials, allow for the more accurate analysis of the system, before deploying, supporting the engineering decision process at the stage of preliminary design. Virtual prototyping of different design based on computer simulations, allows to obtain data impossible to gather in laboratory conditions. It is not only possible to test the different variants but also to perform an in-depth analysis of the interaction between the cutting drum and excavated material as well as the process of haulage by conveyor in case of trajectory and velocity of each particle.

Discrete Element Method (DEM) has found wide application in simulations of issues related to the transport of bulk materials, quarrying and land or mineral alteration (Coetzee et al., 2010; Gröger & Katterfeld, 2007a,b; Gröger et al., 2007). The main objective of this work was to present the possibilities of effective analysis of cooperation between shearer and armored face conveyor, based on a realistic simulation of loading and transportation of excavated material, modeled using discrete element method. Calculations were made with PFC3D software from Itasca.

2. Methodology

2.1. Discrete Element Method

Discrete Element Method is a set of numerical methods and algorithms which allows for the explicit modeling of dynamics of physical systems composed of many separate elements in the free body movement that can come together in contact (Itasca Consulting Group Inc., 2008a). It is now widely used to model the mechanics of granular materials and industrial processes where there are issues related to transportation, processing or storage of particulate materials. Macroscopic behavior of the material is reflected by the selection of micro-parameters characterizing elements as well as the relatively simple rheological models for the contact between them. Micro parameters can be divided into, among others, geometrical and physical (shape, size, density) and constitutive (contact stiffness, damping) (Rojek, 2007). The total number of the necessary micro parameters to be determined depends on the selected contact model. Calculation cycle, shown on Fig. 2, consists of two interdependent algorithms which solve two types of equations:

1. Law of motion – calculation of displacement and velocity changes which results from action of an unbalanced forces acting on element.
2. Force-displacement law (constitutive) – calculation of forces acting on elements being in contact, based on selected contact model.

In both cases, during solving of one type of equation, data obtained on the basis of the previous calculation are known and considered to be constant (Itasca Consulting Group Inc., 2008a).

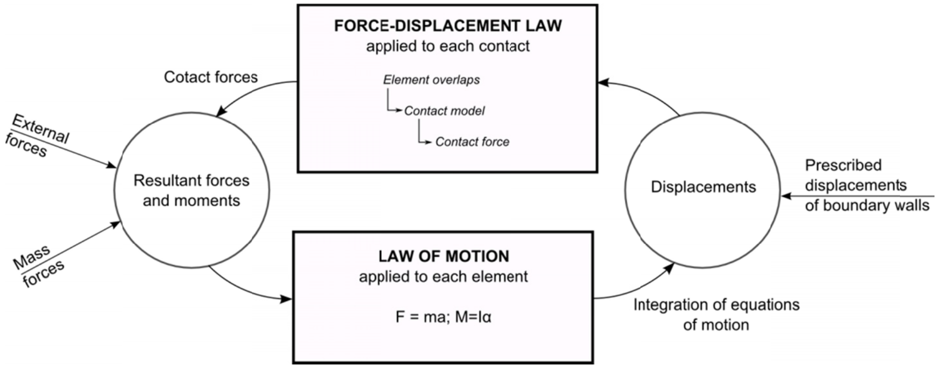


Fig. 2. Schematic representation of DEM calculation cycle

Elements are treated as perfectly rigid, however, overlapping of elements on each other is permitted, which is interpreted as the elastic deformation at the point of contact. For the sake of calculations efficiency and simplifications in the detection of contacts, elements are most commonly represented as a sphere or spheres conglomerates (in the case of the PFC3D). At the beginning of each time step, the set of contacts is updated based on the known positions of the particles and boundary surfaces. Then, for each contact a rheological model (contact model) is applied and contact forces acting on the elements due to their relative movement and position are calculated.

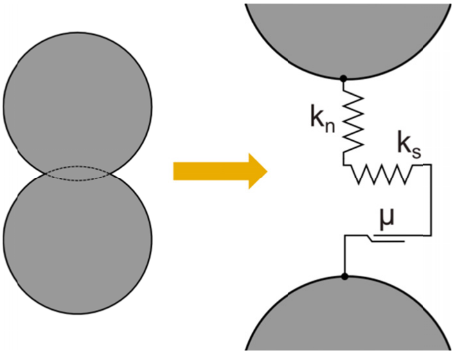


Fig. 3. Application of the contact model

For the simplest case of linear-spring model with friction, contact force is described as follows (Coetzee et al. 2010; Itasca Consulting Group Inc. 2008a):

$$F_i = F_i^n + F_i^s \tag{1}$$

$$F_i^n = K_n U_n n_i \tag{2}$$

$$F_i^s = \min\left\{-k_s \Delta U_s, \mu F_i^n\right\} \tag{3}$$

where:

F_i — contact force acting on element [N];
F_i^n — contact force normal component [N];
F_i^s — contact force tangent component [N];
K_n — contact stiffness in the normal direction [N/m];
k_s — contact stiffness in the tangential direction [N/m];
U_n — relative displacement of the elements in normal direction [m];
ΔU_s — increase of the relative displacement in tangential direction [m],
n_i — unit vector normal to the plane of contact [-];
μ — friction coefficient between elements [-].

Wherein K_n i k_s are particular contact stiffnesses defined by the elastic properties (stiffness) of the two contacting elements (Itasca Consulting Group Inc., 2008a). Knowing the value of the contact force the net force acting on the element is calculated, taking into account the mass forces and any additional external forces. Subsequently the Newton's second law of motion is used to calculate the acceleration and, consequently, to derive the equations of motion for each element. The equations of motion are integrated (central finite difference method) for a very small time step, and the element is placed in a new position. It is followed by a process of detecting new contacts that may arise after the relocation, as well as the elimination of already non-existing (Gröger & Katterfeld, 2007b). Computational cycle is being repeated until the required end time or user defined stop criterion of simulation is achieved.

To reflect the characteristic behavior of the modeled bulk material an appropriate model for the contact should be selected, according to which the resultant force may have additional components to consider such phenomena as, for example adhesion (Gröger & Katterfeld, 2007b). The results of the simulations provide the user with a number of relevant data on physical quantities such as stress, velocity, displacement, etc., of all elements of the system. Detailed description of the method can be found in publications and literature describing the theoretical foundations, application and micro parameters calibration methodology (selection) (Gröger & Katterfeld, 2007a; O'Sullivan, 2011; Itasca Consulting Group Inc., 2008a, b)

2.2. Simulation model setup

2.2.1. Material modeling

The most important part of the simulation model was the properly reflected bulk material. The establishment of the correct material model in the PFC3D requires calibration of its following characteristics:

- particles size and shape,
- density and bulk density
- friction coefficients,
- normal and tangential stiffness
- damping coefficients

Prior to the numerical implementation, it was necessary to define the basic physical and mechanical properties of the material. A representative sample of coal was subjected to standard laboratory tests. First, sieve analysis was performed to determine the size distribution of particles. In a wider range, the cumulative percentage was described by Rossin-Rammler distribution (Brezáni & Zelenák, 2010):

$$P(d) = 1 - e^{\left(-\left(\frac{d}{d_0}\right)^n\right)} \tag{4}$$

where:

$n = 1.7295$ — a measure of the spread of particle sizes (distribution parameter),
$d_0 = 18.1988$ — mean particle size (size parameter).

Afterwards specific density, bulk density and coefficient of friction (internal and external) were determined. Friction coefficients were measured based on direct shear test and with the use of steel chute with adjustable angle. The angle of the chute at the onset of particle slip was recorded. The results obtained are summarized in Table 1.

Table 1

Results of laboratory measurements

Specific density [kg/m^3]	*1412*
Bulk density [kg/m^3]	837
Angle of repose [°]	36
Chute angle at the onset of slip [°]	24,3
External coefficient of friction (steel) – chute [-]	0,45
External coefficient of friction (steel) – direct shear test [-]	0,55
Internal coefficient of friction – direct shear test [-]	1,12
Angle of internal friction [°]	47,84

To obtain physically acceptable response of the material at the macro level it was necessary to choose the appropriate values of the micro-parameters related to selected contact model. This subject is within the interest of researchers for many years, but standard procedures for parameters calibration have not yet been developed. A commonly used approach is to perform laboratory tests of material samples and numerical reflection of the selected tests with iterative change of parameters. Examples of tests which are often modeled (Coetzee & Els, 2009):

- direct shear test,
- uniaxial compression,
- angle of repose test.

In this study a linear-elastic contact model with damping was implemented. With these assumptions, mechanics of material is determined by the normal stiffness k_n, tangential (shear) stiffness k_s, friction coefficient μ, damping factor α (in PFC3D software it is defined as a percentage of critical damping) and the porosity of the sample n (Itasca Consulting Group Inc. 2008a). In order to shorten the calculation time sizes of particles have been increased relative to the actual, but the actual size distribution was maintained (Fig. 4).

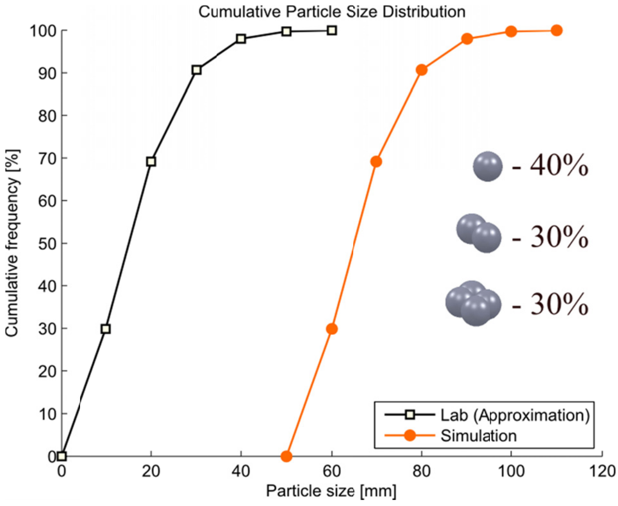
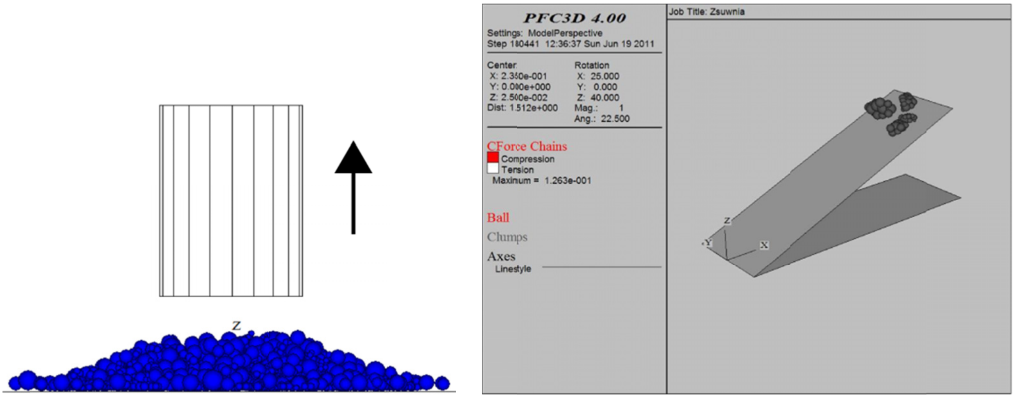


Fig. 4. Size and shape of particles used in simulation

Since the basic geometric unit is a sphere, it involves the problem of the lack of rolling resistance. This problem can be solved in two ways. The first one is a modification of the contact model to incorporate additional moments of resistance based on a given the rolling resistance factor (Wensrich & Katterfeld, 2012). Calibration of another parameter is then needed, and the resulting value of the coefficient of internal friction is a nonlinear function of two parameters, with the assumption of constant micro constitutive parameters. Identification of this function is possible only through a series of simulations. Typically, there are no two unique pair of these micro-parameters, which is a problem while choosing appropriate values. The advantage of this approach is the relatively fast computation time. Another way is to model the conglomerates of spheres by combining individual discrete elements. A simplified shape of real particle is then obtained and rolling friction is modeled explicitly. An additional advantage of this method is that shape of the particle has also influence on nogging. Previous studies have also shown that shape of particles and the moments of inertia related to them have a significant impact on the behavior of a stream of ore during its movement. It is also possible to use the actual values of the coefficient of friction between the particles and the machine elements, obtained from the measurements. The importance of particle shape in DEM modeling has been highlighted in works of many authors (McDowell et al., 2011; Lu & McDowell, 2006). The big disadvantage is the significant increase in computation time. For the simulation purposes simplified shapes were chosen and formed from base spherical elements. 60% of the grains output were modeled that way. The size and shape of the particles were independent variables in the calibration process

As a result of the size scaling, the porosity of the modeled sample was artificially increased relative to the real one. With such porosity obtained at the preset volume of the material (loosely packed), it was necessary to scale particles density to obtain desired bulk density. Normal and shear stiffness of the elements was selected without performing accurate calibration, based on the guidelines found in the literature and previous studies (Czuba et al. 2010a, b). The actual elastic response of the system has therefore been reflected in an approximate manner, which was considered acceptable taking into account the purpose of the study. The coefficients of friction were calibrated based on a simulation of the angle of repose test and chute test (Fig. 5). Adopted micro parameters values are presented in Table 2.



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PFC3D 4.00
Settings:  ModelPerspective
Step 180441  12:36:37 Sun Jun 19 2011

Center:               Rotation
 X: 2.350e-001         X:  25.000
 Y: 0.000e+000         Y:   0.000
 Z: 2.500e-002         Z:  40.000
Dist: 1.512e+000      Mag.:       1
                      Ang.:  22.500

CForce Chains
🟥 Compression
☐ Tension
 Maximum =  1.263e-001

Ball
Clumps
Axes
  Linestyle
```

Fig. 5. Numerical reflection of angle of repose study and chute test

TABLE 2

Chosen values for micro-properties

Contact model	**Linear-elastic with damping**
Specific density [kg/m^3]	1564.5
Coefficient of internal friction	0.75
Coefficient of external friction (steel)	0.32
Normal stiffness k_n [N/m^2]	1.6e6
Shear stiffness k_s [N/m^2]	1.6e5
Damping coefficient [Ns/m]	0.95

A very important aspect of the preparation of the model is appropriate packing of particles. It can be achieved by means of dynamic or geometric algorithms. Dynamic algorithms are relatively simple to implement and are using calculation cycle of the program for the preparation of packing. The simplest example is the densification of the material through the gravity settlement of successively dropped layers of elements. Other dynamic methods, rely on generating elements of a given size in a certain area bounded by walls, and then compaction of assembly through their forced, quasi-static movement (triaxial compression). The biggest advantage of dynamic algorithms is the possibility of obtaining a predetermined size distribution of particles. The disadvantage is a long time to prepare and the occurrence of initial „locked-in" contact forces in the system, corresponding to the model of initial stresses, which in reality does not exist. These methods have difficulties obtaining a sufficiently large value of the coordination number, understood as the number of contacts for each of the elements. Furthermore, it is not possible to obtain an assembly with low porosity. Geometric algorithms, also called constructive, do not require carrying out a DEM calculation cycle. Components are placed on the basis of the geometric relationship, often with the use of pre-prepared mesh. Geometric methods are much faster but more difficult to implement, however it is possible to obtain a very low porosity and a large coordination number. For the purpose of this work the material in a desired configuration and the packing has been generated based on dynamic algorithm called radius expansion (Itasca Consulting Group, Inc., 2008b). Then, a file with information about the location and size of the particles for the use in the target simulation was prepared.

2.2.2. Geometry modeling

Simple geometric elements such as flat walls, cylinders, or rectangles can be successfully created directly in PFC3D. Implementation of more complex geometry is difficult and time-consuming. PFC3D program allows one to import CAD models created in external programs such as Autodesk Inventor or SolidWorks, saved in STL format. Reducing the number of walls making up the geometric model used in the simulation significantly increases the speed of computation by reducing the number of objects that can potentially interact with the material and hence, must be taken into account when searching for contacts. It was therefore reasonable to simplify the geometric model while maintaining the level of detail which may have a direct impact on the analyzed phenomenon. Movement of wall elements is achieved by defining their properties in the program, with specific functions. The area of the simulation has been limited so it was necessary to schedule when a geometry (eg flight bar) is generated and participates in the simulation, and when it should be removed. The user may use built-in programming language

FISH, which enables to write functions describing such operations. Figure 6 shows geometries of the shearer and conveyor after simplification.

TABLE 3

Kinematic and geometric parameters

Feed speed [m/min]	10
Cutter drum rotational speed [obr/min]	59
Flight bar speed [m/s]	1.5
Flight bar pitch [m]	0.75
Cutter drum diameter [mm]	1300
Cutter drum diameter with cutting tools [mm]	1400
Coal bed height [m]	1.5
Shearing depth [m]	0.7

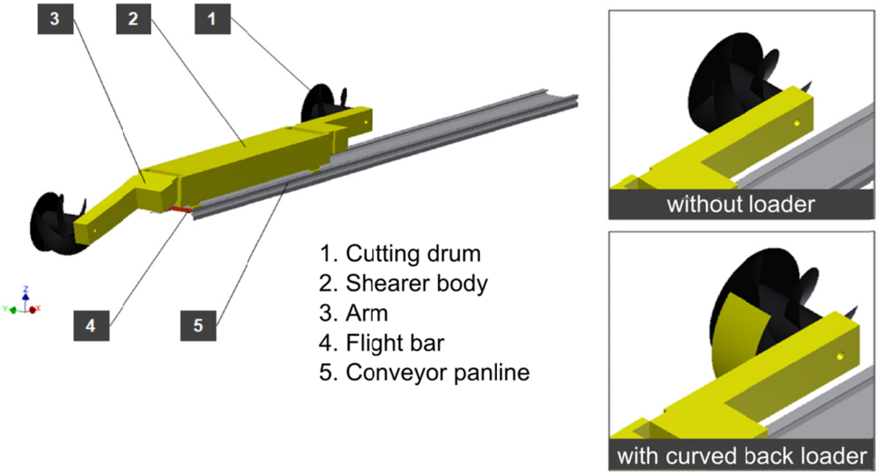

Fig. 6. Simplified shearer and conveyor geometries

2.2.3. Simulation assumptions

To develop a simulation model, the following simplifying assumptions were adopted:

- For a chosen conditions, shearer speed is constant, and any resulting resistance to motion do not cause its change.
- Generation of material excavated by cutting drum was not the subject of the simulation. Parameters of stream were calculated based on the analytical model describing the process of mining with the use of cutting drums.
- Particles are not crushable.
- Simulation time – 15 seconds.

The first assumption is justified taking into account commonly used shearer powers and characteristics of drives that guarantee the maintenance of constant speed of the shearer and rotational speed of cutting drum. The second assumption stems from the fact that the modeling of the entire cutting process is very complicated, especially because of the preparation of the numerical model of rock bed by using additional bonds between the elements which need sophisticated calibration. Currently, models of this type are used in analyses focusing on single tool cutting, also because they are computationally demanding. It was considered sufficient to develop an algorithm that allows the program to calculate and generate particles moving in the space between coal seam and patches and the cutting drum body hub. For this reason the geometric model of cutting drum was limited to a diameter of 1300 mm, which is the diameter of the loading lobes, excluding cutters. The mathematical model describing loading efficiency of stream of excavated material from the cutting area on the conveyor was developed based on existing theoretical models of mining with the use of cutting drums (Opolski, 1966; Krauze, 2000). The essence of algorithm is described below.

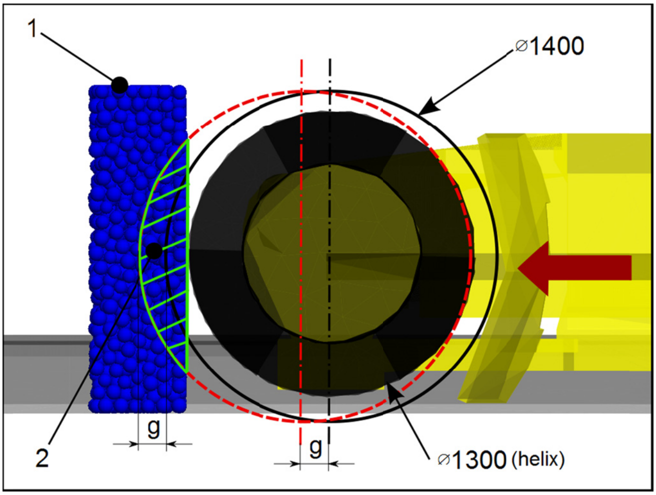

Fig. 7. Adopted model of mining process

On figure 7 the shearer is shown in close proximity to previously generated portion of the material (coal bed face) 1. In the initial stage, all elements have locked all degrees of freedom, i.e. are fixed with no possibility of movement. Knowing the feed rate of shearer as well as the rotational speed of the cutting drum, and assuming one line of cutting picks, the maximum depth of cut ($g_{\max}$) is calculated based on the condition of equality of time needed to move shearer of about $g_{\max}$ and full rotation of the cutting drum:

$$g_{\max} = v_{pos} \cdot t_{obr} \tag{5}$$

$$2\pi = \omega \cdot t_{obr} \tag{6}$$

Comparing both expressions and taking into account that $\omega = 2\pi n$, it can be calculated:

$$g_{\max} = \frac{v_{pos}}{n} \tag{7}$$

Knowing $g_{\max}$ and time of one rotation t_{obr}, and knowing that the diameter of the cutting drum with cutting picks is 1400 mm, prior to each shift of the cutting drum of $g_{\max}$, a suitable amount of material is prepared 2. Such "forward" preparation results in releasing of degrees of freedom of the material, which theoretically should be excavated during the next shift and rotation of cutting drum (shaded in green). In practice, the excavation process does not take place but only the loading of the theoretical amount of excavated loosened material.

3. Results and discussion

Positions and speed of individual elements were recorded during the simulation. This information allowed to perform an analysis of motion of excavated material in the course of cooperation between a shearer and armored face conveyor. Qualitative results are analyzed conveniently in the form of movies composed from screenshots made from visualization of simulation data in equal intervals. It is a commonly used methodology in the case of DEM simulation. It is possible to observe the entire stream movement as well as the trajectory of individual particles. Colors are assigned to particles depending on the calculated speed, which makes more convenient observation of the velocity distribution of individual grains in the stream of material.

Figure 8a presents up cutting mining and figure 8b presents down cutting mining. It can be seen that in the case of up cutting mining the loading process is more effective. Stream of coal which is fed to the conveyor is more homogeneous and fills the space between the flight bars evenly and completely. The volume of material remaining in the area behind cutting drum body is less than during down cutting mining. It is also confirmed by the formation of excavated material pile behind a conveyor. Using the results, it can be determined what should be the height of the back plate to prevent spillage of the material onto the path where wall crew is moving.

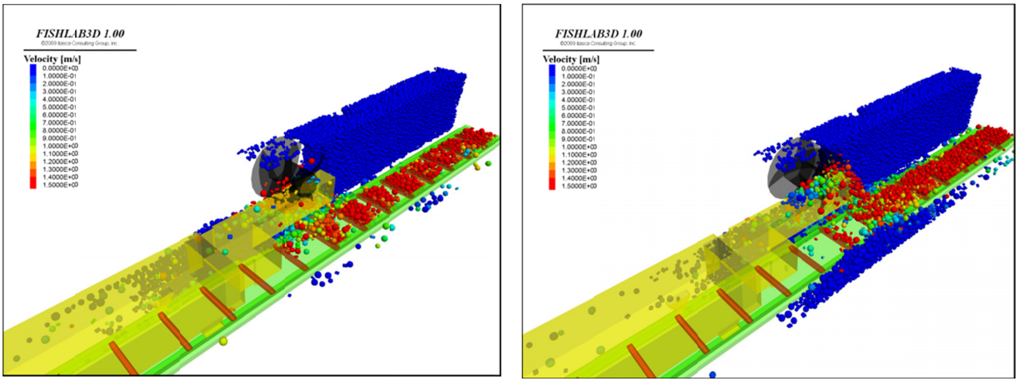

Fig. 8. Qualitative comparison of two mining methods: Down cutting (top) and up cutting (bottom). Colors represents particles velocities

In the case of down cutting mining amount of material remaining from the side wall is less than during up cutting mining (Fig. 9). Excavated material must be loaded by the second cutting drum or wedges installed on the conveyor panlines, during movement of conveyor toward coal wall.

The negative effect of up cutting is the appearance of large quantities of excavated material on the arm of the shearer. Despite the greater efficiency of loading, flow of the stream is more disturbed causing the coal lumps to be thrown over the drum body, forming a layer of material on the arm. Stream of material is divided into three major paths (Fig. 10): main – falling onto a conveyor (1), stream of material falling on shearer arm (2) and rear stream directed behind the cutting drum (3). In the case of flat beds, this may constitute a potential risk associated with the formation of a natural wedge between the arm and the ceiling which could increase the resistance to motion.

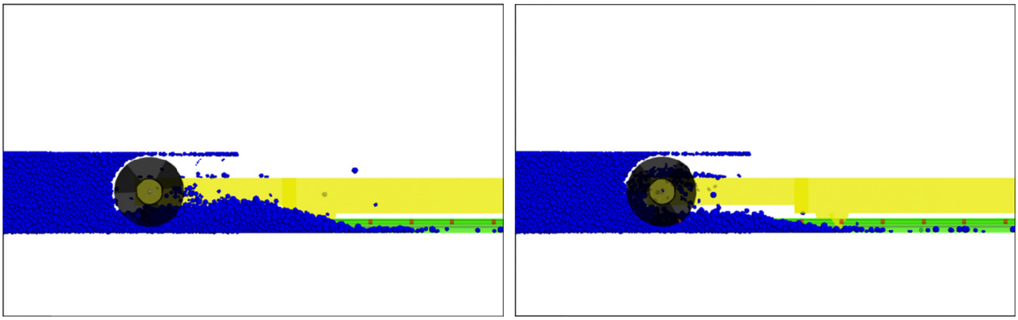

Fig. 9. Unloaded material remaining behind the cutting drum. Down cutting (left) and up cutting (right)

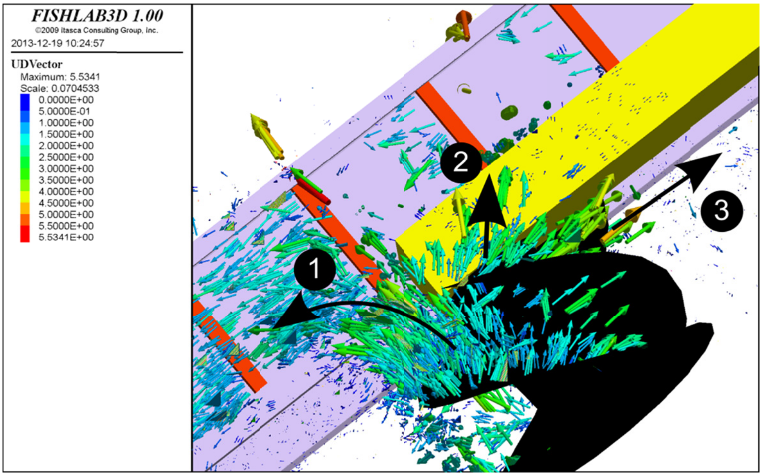

Fig. 10. Velocity vectors of coal particles within area of the cutting drum body in case of up cutting

Loading area in this case is greatly reduced, due to the height of the coal bed. Additional loading area constraints may be influenced by the conveyor bends and shearer geometry. The results of the simulation allowed for an analysis of the operation of the machine with the given parameters and to estimate that there will be no choking. Figure 11 presents a view from the outside of the shearer, showing the distribution of the material in the space between the lobes of the cutting drum. The walls colored in grey represent simulation area, equivalent to the actual restrictions in the working area. It should be emphasized that this type of observation in case of real object would not be possible, so the results are a valuable resource when assessing the limits of specific parameters such as feed rate or cutting drum rotational speed.

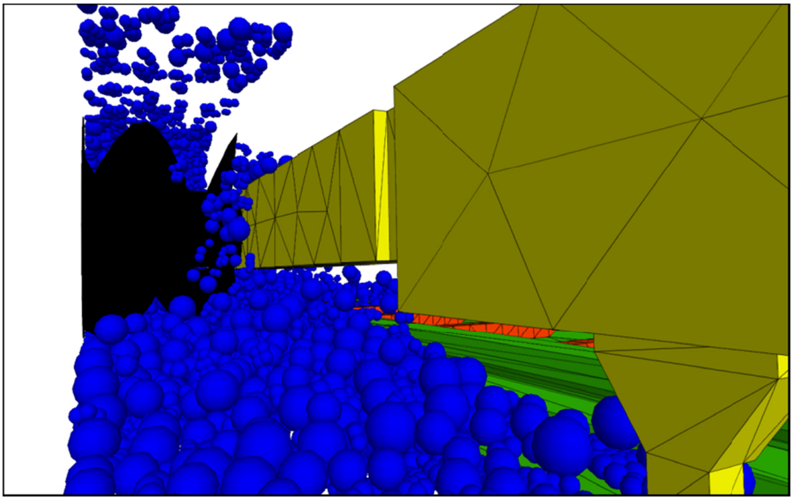

Fig. 11. Loading area

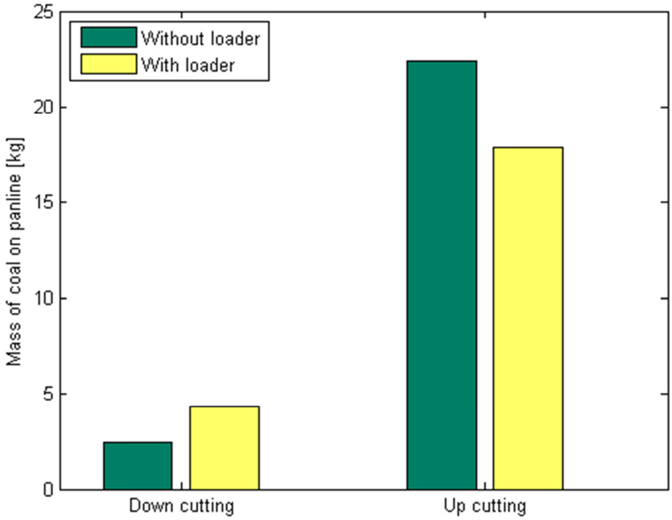

Fig. 12 Mass of coal on the conveyor in case of shearer setup and mining method

In order to perform additional quantitative verification, mass of the excavated material located on a conveyor panline was measured after a predetermined time. Obtained values, due to the simplification related to the grain size, are not relevant for the real object. However, it was possible to compare simulation results for different variants of work and shearer setup in case of the same inputs. Quantitative results indicate significantly higher efficiency of the system during up cutting mining.

Despite the lack of verification on a real object, operational experience resulting from the observation of working shearers, confirm the correctness of the results in terms of material stream movement. The occurrence of certain adverse events can be observed, such as spillage of the material, accumulation of excavated material from the side walls or on a shoulder of the shearer. It is therefore possible to determine when such events occur in case of coal bed conditions and geometrical characteristic of the shearer-conveyor system, as well as kinematic parameters of these machines.

4. Summary

The results indicate that the proposed simulation based study method may be an effective tool to verify and optimize the design solutions of mining machinery. This is important not only in the economic aspect but also in case of work environment protection. The simulation results can also be useful to verify selected parameters of the mining shearer working in certain geological conditions. In this study a series of numerical simplifications were applied, in particular with regard to the shape and size of the particles. There also not have been performed a rigorous selection of micro parameters, which were chosen based partly on the results from the literature, without carrying out all the required calibration steps. Therefore, obtained results can be used only for relative comparison of the effect of selected parameters on the response of the model, without reference to the actual object. Based on the simulation results it can be concluded that in the case of shearers working in flat beds, up cutting mining is preferred. In case of down cutting mining, efficiency of loading is much lower. It is related to the stream trajectory, which in case of this cutting method and constrained loading area is formed in such way that a lot of material is directed behind the cutting drum. In addition, the use of curved back loader increases the amount of loaded coal for down cutting mining, but interestingly, not in the case of up cutting mining. Despite the lack of verification with the real object, experience from observations of the shearers, confirms adequacy of obtained results which are significant enough to be used in practical analysis and synthesis of cutting, loading and transport processes in longwall mining systems. It would be worth continuing research to perform more advanced analyzes, which will require precise calibration of the model parameters and the use of a wider range of particle sizes and complex shapes. The spectrum referred to, could also take into account other particles with different mechanical physical properties which occur in practice in certain geological conditions. It would be possible then to analyze motion resistances. Interesting directions for further work in the aspect of DEM modeling of mining shearers are, among others. Simulations of airborne dust (in conjunction with CFD), wear of machine parts, crushing of material grains as well as fully featured analysis of cutting the coal face. Rock being cutted is then represented by elements connected to each other with bonds of a specified strength and stiffness. This approach allows to directly reflect actual fracture mechanics of material, without the need for additional constitutive relations as in the Finite Element Method. Some limitations in such cases are required large computing power.

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