The Mutual Effect of Reciprocally Moving Geokhod and Geological Environment Studied by the Discrete Element Method in Software PFC3D 5.00

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Abstract. A numerical experiment procedure of geokhod traverse in the geological environment, based on software PFC3D 5.00 is presented in the paper; the interpretation of numerical experiment results is provided.

Introduction

At present a new generation of geokhod is being developed by researchers of Yurga Institute of Technology, TPU affiliate [1]. The principles of operation, regularities of its traverse in the geological environment are studied [2], parameters of its transmission [3-6], working units [7-8], pump station [9], as well as those of casing of geokhod sections [10] are being determined.

A pilot sample of geokhod is to be tested soon when tunneling mines with a diameter of 3.2 m. Results of tests will be used for making a decision regarding its further modernization or serial production organization of the developed sample, as well as outlooks of prospective investigations should be done. However, it is obvious at this moment geokhod, having a new operation principle based on the mutual effect with the geological environment requires further study in order to improve its constructions.

One of the promising ways of research into the traverse of geokhod in the geological environment is a quite new method of discrete elements (MDE). MDE is a set of numerical methods intended for calculating a lot of discrete particles. Having been used in 1971 first to solve problems of rock mechanics, this method is widely applied now to solve geo-mechanical problems. A number of software is available currently for MDE-simulation of processes and solution of engineering, applied and fundamental scientific problems. The most accepted and widely used software is listed below: YADE; LIGGGHTS; Chute Maven; EDEM; PFC3D etc.

A wide range of software is available as they support solution of special tasks. The software programs differ mainly in functional capabilities, tasks to be solved, process, used operation system, a possibility of splitting up calculation, which is necessary for the complete use of a multi-process equipment (efficient computing machines).

One of leading companies, manufacturing software for MDE implementation, is Itasca (Itasca Consulting Group, Inc., USA). This company is oriented at the development of following software

programs: FLAC/FLAC3D, PFC2D/PFC3D, KUBRIX, 3DEC, UDEC. A wide range of offered programs support solution of almost all MED-solved geo-mechanical problems. We used software PFC3D, version 5.00 to carry out numerical experiment of geokhod traverse in the geological environment. Simulation of various physical processes for solution of scientific and engineering problems is based on this software, used in diverse fields of science and production: process industry, mining industry, and engineering and geological prospecting sciences etc. This software is selected due to its functional capabilities in the field of modelling the mutual effect of solids and discrete particles. Operation system Windows is used to run this program, making it widely applied all over the world, moreover, it supports splitting up the calculations. An advantage worth emphasizing is compatibility of CAD-system file with accepted formats (format STL).

Methodology of numerical experiments
When carrying out a numerical experiment by software PFC3D 5.00 assumptions listed below are made:
   - particles have six degrees of freedom;
    - particles are rigid and resist to deformation when coming into contact;
    - the environment to be modeled is isotropic and homogenous;
    - particles of any geometrical form can be applied in principle, but spherical particles are most efficient for the case under consideration;
    - particles interact according to the pre-set contact law when contacting;
    - external forces can be applied to particles, e.g. gravity force;
    - contacts between particles can be broken or re-formed when carrying out experiments.
    The experiment comprises six phases:
    1. Generation of particles (development of the geological environment model) and assignment of boundary and starting conditions.
    2. Determination of a contact type of particle to particle and particle to boundary.
    3. Calculation of contact forces and torsion moments of all interacting particles.
    4. Calculation of accelerations, speeds, values of displacement and rotation frequencies of all particles.
    5. Calculation of new positions for all particles.
    6. Phases 2 to 5 are repeated at time interval till approaching the boundary conditions.

The development of a design model
A design model of geokhod was developed in order to conduct MDE-experiments of geokhod traverse in the geological environment by software PFC3D 5.00. A design model of geokhod is made in software SolidWorks and exported in format STL (Figure 1).
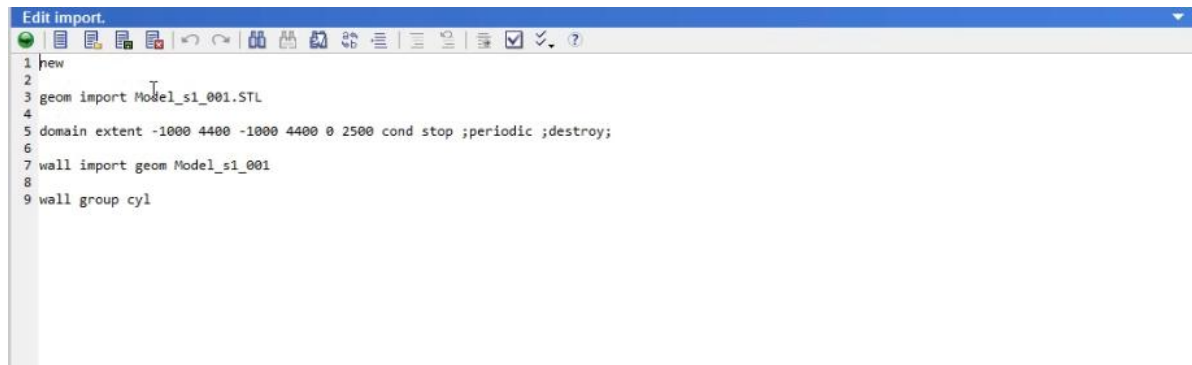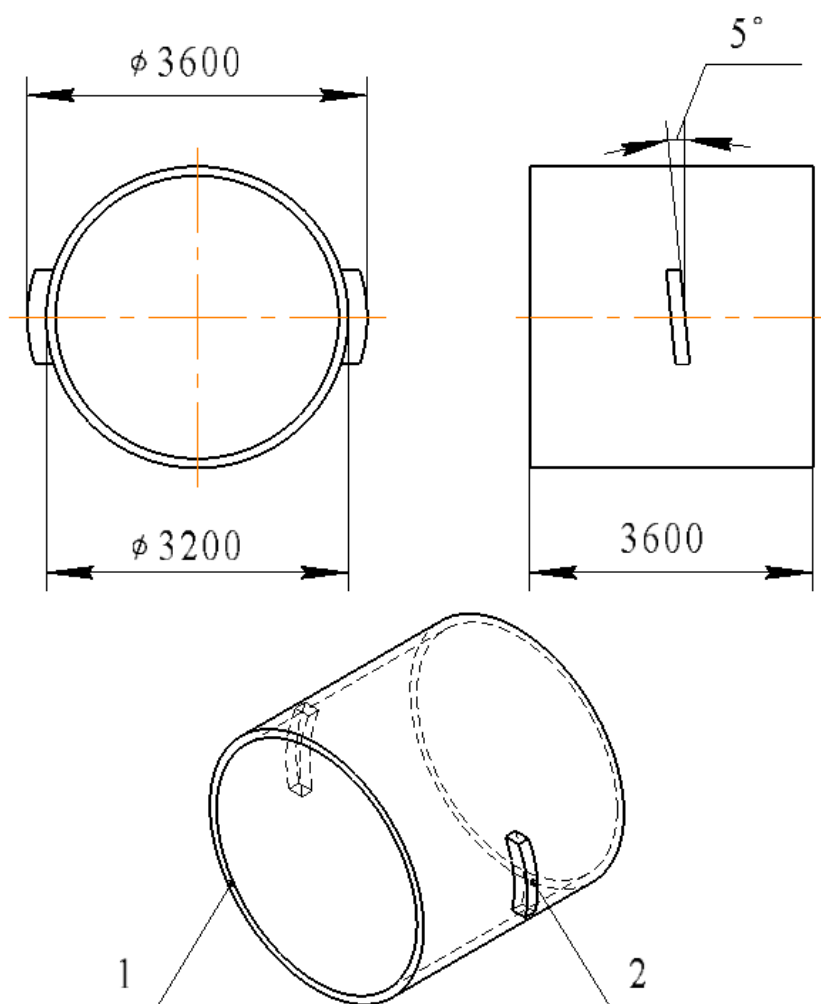
1 – body; 2 – propulsive agent
Figure 1. A design model of geokhod

A design model is a simplified structure of geokhod head section with two propulsive agents. The dimensions of the design model taken in absolute magnitudes are in line with those of geokhod. Propulsive agents are sections of a helical surface; an inclination angle to the perpendicular of traverse axis equals the same angle of geokhod. The model exported into format STL is loaded as an imported geometry in software PFC3D 5.00.

Assignment of modelling boundary conditions
A distinctive feature of system PFC3D 5.00 is a capability of function setting by program using pre-set algorithms and commands in special text files instead of visual function setting by the interface. The development of modelling boundary conditions is based on the same principle. Figure 2 provides a command sequence, which imports the model of geokhod and modelling boundary conditions are developed in form of a domain (command "domain") and "walls" (command "wall").

Figure 2. A sequence of commands for import of a design model and development of boundary conditions

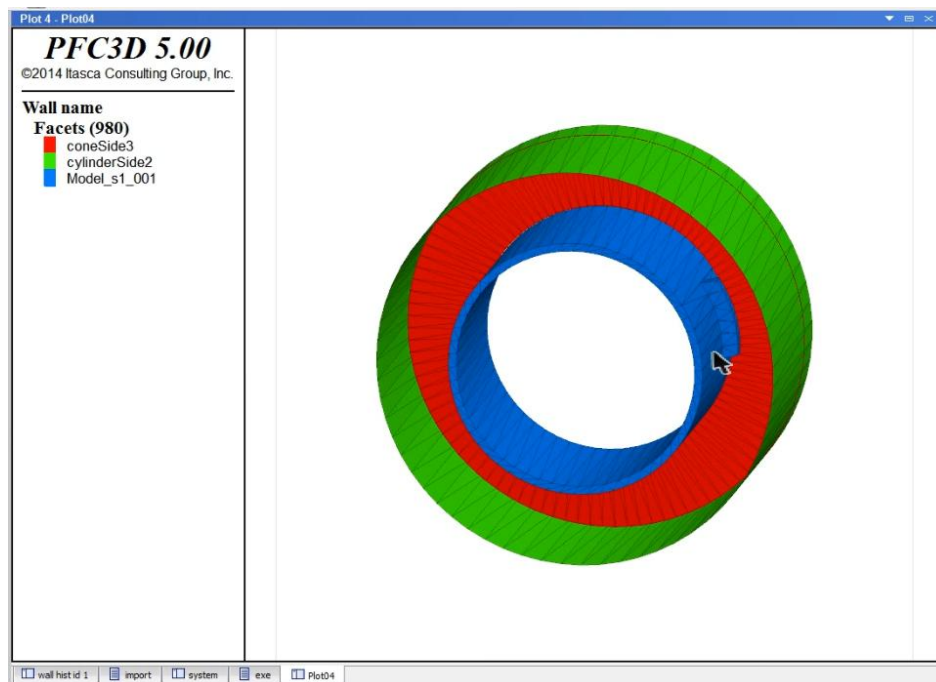The result of implementing commands is given in Figure 3.

Figure 3. Import of the model and development of boundary conditions

An imported design model of geokhod is given blue in Figure 3, green is boundaries of a "domain" – field, where particles will be developed (area of geological environment modelling), a "wall" is given red – a boundary of discrete elements traverse when modelling the geological environment. Properties of a "domain" differ from those of a "wall" because the "wall" can be permeable or it tends to destroy discrete elements out of its boundaries. In this case particles out of the "wall" are cancelled due to its properties. Dimensions of a "domain" are determined taking into consideration a probable area, where the mutual effect of propulsive agent and geological environment influences displacement and deformation of discrete elements. The dimensions of the domain: diameter (4400 mm), length (2500 mm).

Modelling the geological environment
Modelling is one of the most important experimental phases, since parameters, which are as alike those of real rocks as possible, are to be built into the geological environment to be simulated. Moreover, a number of discrete elements have a significant effect on computer capacity and its operation time when calculating experimental results. It is impossible to take into account all the parameters because of deficient data on geokhod operation at this stage; so a simplified model of the geological environment is accepted. This model includes a minimal set of parameters of the geological environment to be modeled, although accurate data can be obtained on their base; the geological environment is anisotropic and homogenous as well. In this case a geological environment with 75 000 discrete elements is simulated in the "domain". The number of particles is selected empirically while carrying out similar experiments by computer with CPU clock 3.7 GHz, RAM memory space 16 GB; and the experiment lasted approximately 6-8 hours. An element size is varied from 5 to 17 mm, on assumption of complete filling "domain" – "wall" – and design model space.

In Figure 4 there is a sequence of commands presented to create discrete elements, which make a geological environment to be modeled, as well as an algorithm of using these discrete elements to fill the space of geokhod design model and "walls" of "a domain".


```
Edit Balls_gen.p3dat

 1   ball generate id 1 75000 rad 0.010  tries 100000000 range ...
&2      cylinder end1 1.800 1.600 0 end2 1.800 1.600 1.955 radius 1.800 not ...
&3      cylinder end1 1.800 1.600 0 end2 1.800 1.600 1.955 radius 2.450
 4
 5   save ini75k_B.sav
```
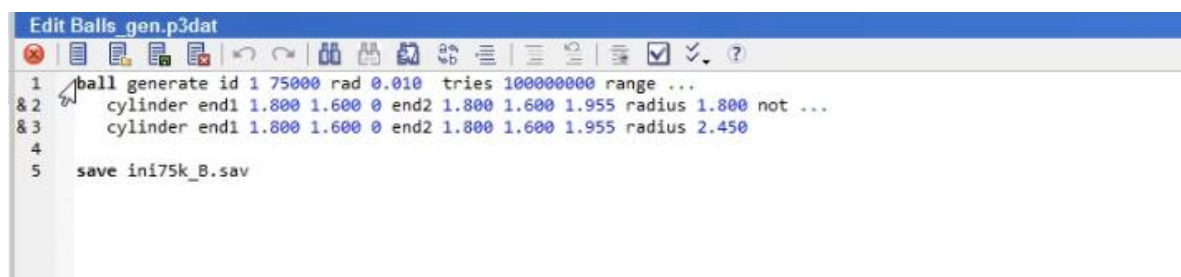
Figure 4. Development of discrete elements

In Figure 5 there is a fragment of a file presented, which includes commands assigning properties of experiment elements and ways of their mutual effect:
  - a rule of discrete element mutual effect («linear bond» [1]);
  - a rule, describing the mutual effect of discrete elements and the model edge («linear»);
  - properties of contacting elements (variables «kn», «ks», «dp_ratio» [1]);
  - properties of contacting discrete elements (variables «pb_kn», «pb_ks», «pb_ten», «pb_coh» [1]);
  - properties of model "walls" (variables «kn», «ks», «froc» [1]).

An algorithm is also presented, which increases cyclically the diameter of a ball-shaped discrete element 5 to 17 mm with 1 mm interval. This algorithm supports gaining the sizes of discrete elements as soon as they fill the required space, although the contact force between them does not exceed pre-set values.

Figure 5. Assigning properties of numerical experiment constituents and algorithm of filling the model space by discrete elements

As soon as an algorithm is developed a model of the geological environment is created. Intermediate calculations of the geological environmental properties are given in Figure 6.
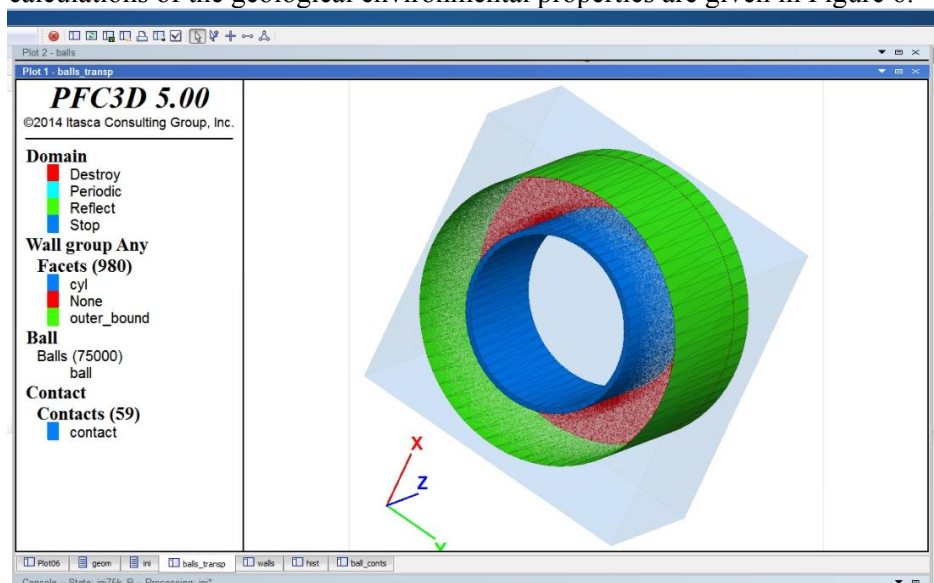

Figure 6. Intermediate calculations of geological environmental properties

Minimal discrete elements are shown white in Figure 6 at the start of modelling. There is a result of modelling the geological environment shown in Figure 7.
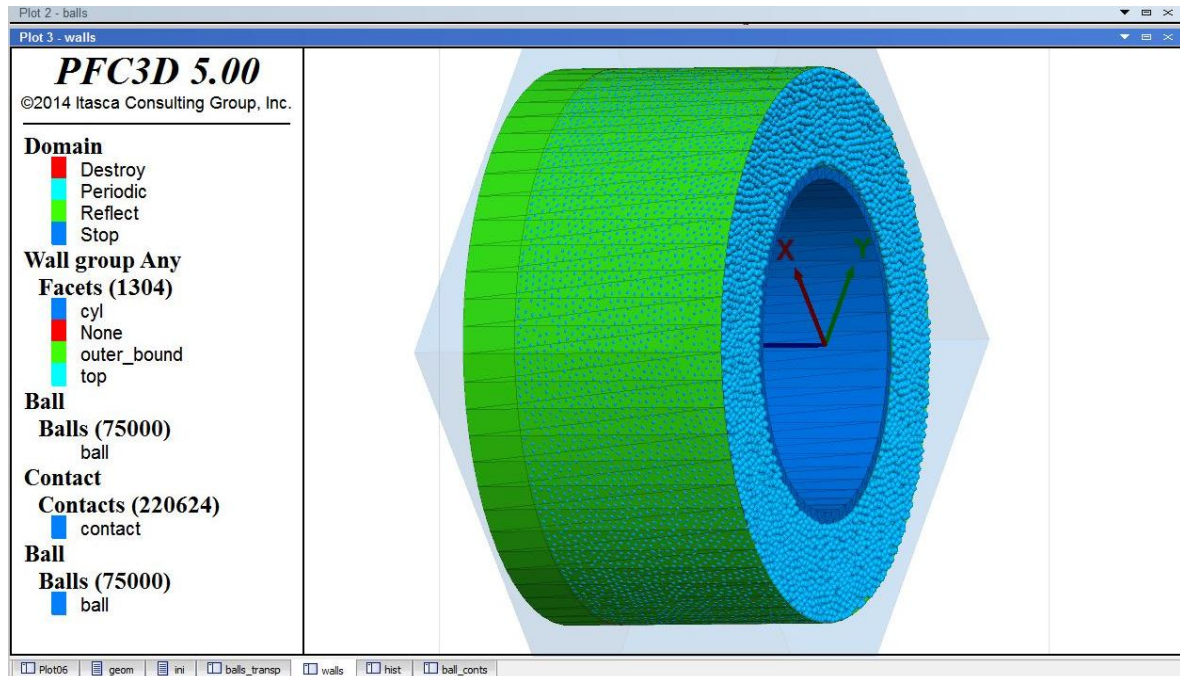

Figure 7. Computational results of geological environmental properties

It is seen in Figure 7 ball-shaped discrete elements fill the space of design model and modeling edges.

Numerical experiment
A numerical experiment is required to simulate the mutual effect of moving geokhod and geological environment. The software supports visualization of geokhod traverse in the modeled geological environment, as well as real-time tracking parameters of phenomena, occurring in the process of traverse such as diagrams of breaking ties between discrete elements, graphs of changing force parameters both on geokhod surface and in the geological environment etc. A simulating algorithm of the geokhod head section rotation with a real frequency (Figure 8) is developed for translational displacement and rotation. A real rotation frequency of geokhod is set 6 revolutions per hour.

```
Edit Rotation.p3dat
 1    res ini75k_B_5-17_bonded.sav
 2
 3    wall generate group inner_bound cylinder base 1.800 1.600 0 ...
&4        axis 0 0 1 height 2.500 radius 1.600 cap false
 5    wall prop kn 2e10 ks 2e10 fric 0.1 range group inner_bound
 6
 7    wall attr centrotation 1.800 1.600 0 range group cyl
 8
 9    wall history xcontactf id 1
10
11    wall history contactforce id 1
12
13    wall history velocity id 1
14
15    wall history spin id 1
16
17    def inirot
18      loop i(1,10)
19        rotvel_   = i*0.01309/10.
20        forwardvel_ = i*0.00167/10.
21        command
22          wall attr spin 0 0 @rotvel_ range group cyl
23          wall attr vel 0 0 @forwardvel_ range group cyl
24        end_command
25      end_loop
26    end
27    @inirot
28
29    set timestep scale
30
31    solve time 480
32    save rotation_end.sav
```

Figure 8. Algorithm of rotation and translational displacement of a geokhod model

As soon as an algorithm of rotation is developed a numerical experiment is conducted. Carrying out an experiment the algorithm involves one full revolution of a geokhod model round its axis.

Results of the numerical experiment

As a result of numerical experiment a pattern is developed by software PFC3D 5.00, which represents the mutual effect of a design model with discrete elements, modelling the geological environment, and supports displaying various parameters of this interaction in form of diagrams.

A diagram of contact forces is given in Figure 9, which arise in the geological environmental model (in discrete elements), when geokhod rotating.
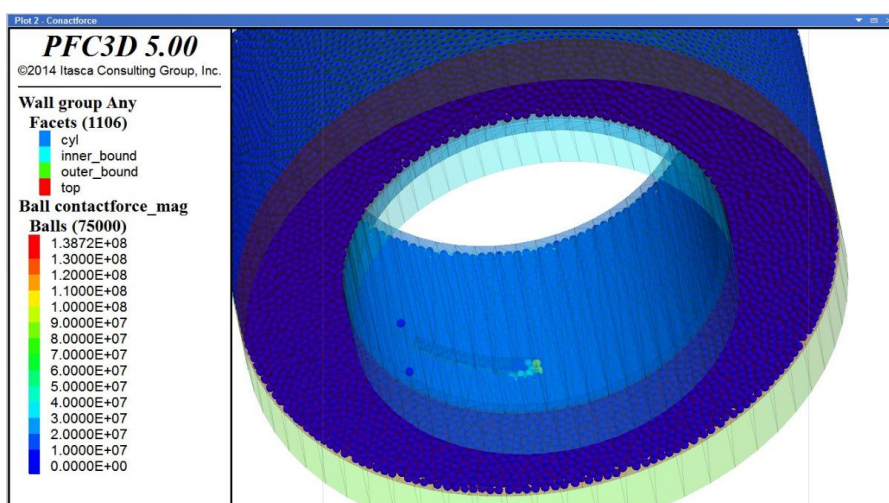

Figure 9. A diagram of contact forces in the geological environment (in discrete elements) when propulsive agent moving

The design model of geokhod is presented transparent (Figure 9) for better visualization on the diagram. The diagram shows a propulsive agent of geokhod model, moving among discrete elements

of the rock mass. Software PFC3D 5.00 allows of following a changeable numerical value of variable to be measured. Varying values of forces on the contact surface of geological environment and propulsive agent, as well as in the geological environment are given in various colors. Minimal contact forces are given blue in this diagram, they equal 0.0000E+00 (Figure 9), and gradient colors of red present rising contact forces. Maximal contact forces of 1.3872E+08 or $1.3872 \cdot 10^8$ N are given in red. The maximal contact forces shown on the diagram are there in font of the propulsive agent, where geological environment is broken.

Software PFC3D 5.00 supports detecting forces arising when breaking the ties of discrete elements (internal stresses in geological environment). Other possibilities for representation of geological environmental model are provided. A diagram of contact forces, representing the geological environment by the ties between discrete elements not by elements themselves is given in Figure 10.
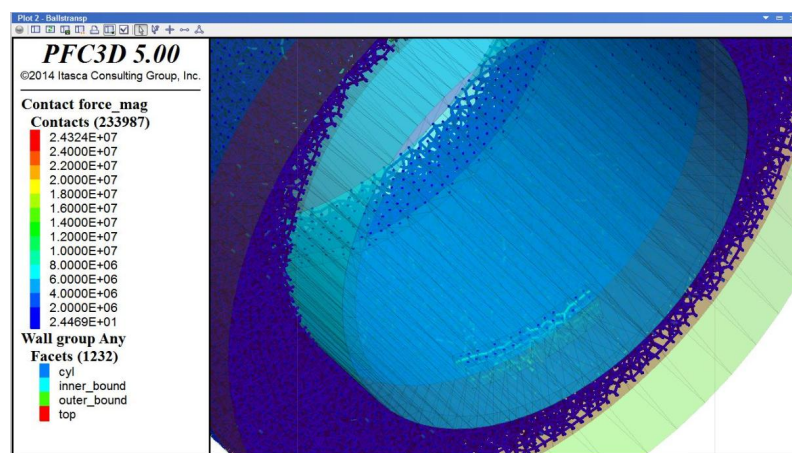

Figure 10. A diagram of contact forces in the geological environment (breaking the ties) when a propulsive agent moving

The maximal contact forces of $2.4324 \cdot 10^7$ N arise in the zone of moving propulsive agent when breaking the ties between discrete elements (Figure 10).

The software makes it also possible to determine other variables, e.g. a velocity diagram of geological environmental particles (discrete elements) is obtained when moving a geokhod model (Figure 11).
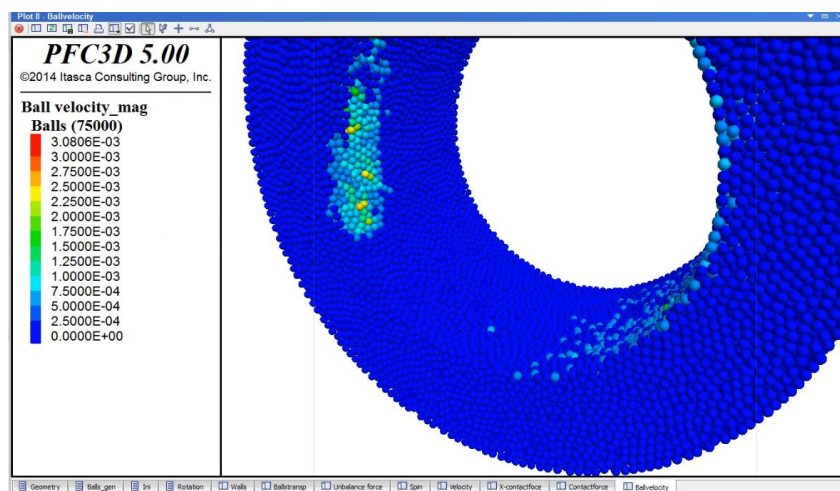

Figure 11. A velocity diagram of discrete elements when geokhod traverse

The maximal velocity of discrete elements hardly exceeds 3.0806·10-3 m/s.

The obtained diagrams and values represent only some capabilities of the software. It can be used to determine such parameters as stresses in the geological environment along various axes, stresses on the model surfaces, and value and velocity vector of discrete elements etc.

Processing the results of numerical experiment

Software PFC3D 5.00 supports plotting the results of numerical experiment. Here, the results are given as plotted functions of calculation steps (variable "Step"). The value of steps of calculation (variable "Step") is directly dependent on computer capacity and can be seen as analogue of experiment period.

Values to be measured vary according to the rotation angle of the propulsive agent in this experiment; however, angular velocity of rotation is uniform and period or the quantity of computation steps (variable "Step") are accepted as argument of function.

A plot of changing contact forces on the cylindrical surface of a design model is given in Figure 12 (on the body surface of the geokhod head section) according to the calculation steps ("Step"), in this case the length of X-axis is in line with 360° revolution of a model.
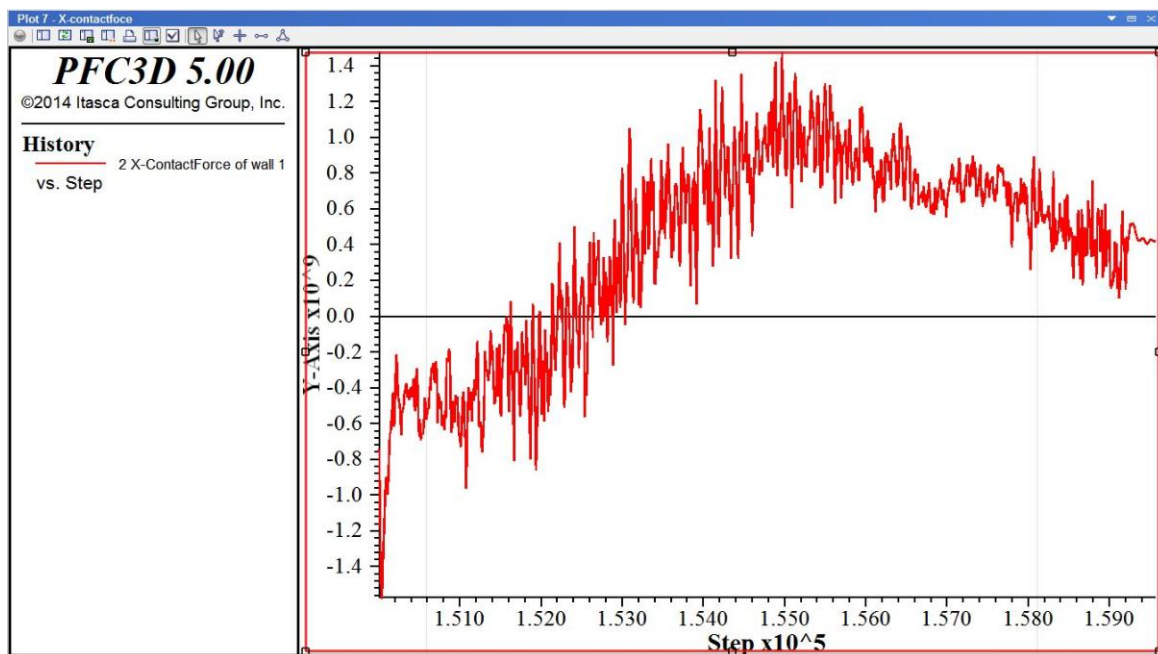

Figure 12. A plot of changing contact forces

The value of contact forces on the geokhod surface is changeable, reaching its maximum 1.4·109 N when rotating. A negative value of a contact force indicates its direction, which is reverse to traverse of a design model.

A force, arising on the inner surface of a propulsive agent is also an important force parameter. This force is important when forming forces required for traverse. A plot showing the change of contact forces on the surface of the propulsive agent is given in Figure 13.
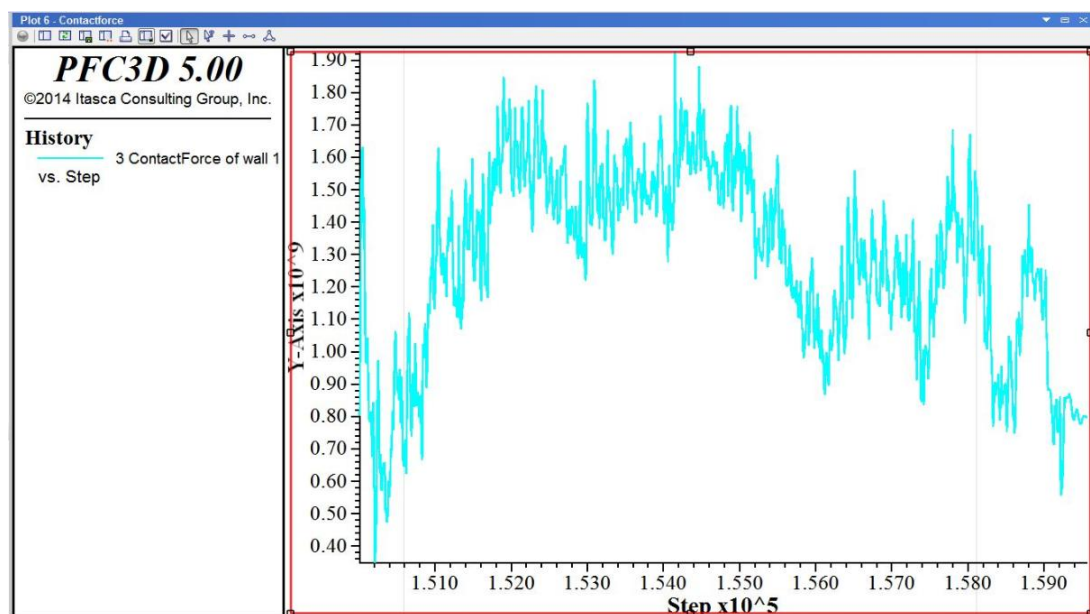
Figure 13. A plot of changing contact forces on the surface of a propulsive agent

Contact forces vary in a wide range when rotating. An average value of contact forces is $1.2 \cdot 109$ N with its maximum of $1.9 \cdot 109$ N.

Conclusions
A possibility in principle to use software PFC3D 5.00 for modelling geokhod traverse in the geological environment was revealed in the work. The principles of numerical experiment based on discrete element method are outlined to simulate the mutual action of moving geokhod and geological environment. As a result the following shortcomings of software PFC3D 5.00 were detected:
   - the software is strongly dependent on computer capacity, changing quantity of discrete elements to be processed requires longer experiments (the experiment under consideration involved 75 000 discrete elements, taking 10-12 hours for one rotation of geokhod), improvement of experimental accuracy or input data variation necessitates the increase in discrete elements, resulting in significant growth of computation time;
   - the experiments detected incomplete compliance of the software with real physical processes, for instance, an axial force arises and pushes geokhod ahead in real conditions when inclination angles of propulsive agents are 5 degrees (Figure 1) and the model of geokhod rotates, but specifics of software PFC3D 5.00 allows no axial force.
   The following measures were proposed to eliminate these shortcomings:
   - parallel computations are available in software PFC3D 5.00 when carrying out experiments, making possible its use by powerful supercomputers like "cluster" and reducing the time of computations;
   - software PFC3D 5.00 supports control over obtained data and development of an algorithm of progressive traverse of geokhod according to forces arising on the propulsive agent.
   The advantages of software PFC3D 5.00 when modelling geokhod traverse in the geological environment are as follows:
   - substantial reduction of costs as against field simulation;
   - a wide range of obtained experimental data;
   - a possibility of varying parameters of the geological environment to be modeled (anisotropy of the geological environment can be pre-set);

- values of experimental data both in the geological environment and on the contacting surfaces of geokhod can be obtained;
- simplicity of obtaining experimental data.

References
[1]   Aksenov, V. V., Walter, A. V., Gordeyev, A. A., & Kosovets, A. V., Classification of geokhod units and systems based on product cost analysis and estimation for a prototype model production, In IOP Conference Series: Materials Science and Engineering. 379 (2015).
[2]   A.B. Efremenkov, V.Yu. Timofeev. Determination of Necessary Forces for Geokhod Movement, 7th International Forum on Strategic Technology IFOST2012, (2012) 211-214.
[3]   Timofeev V. Y., Aksenov V. V., Galjamova J. I. Determination of parameters of roller of wave transmission with intermediate rolling bodies with hollow shaft for geokhod // Applied Mechanics and Materials. – Trans Tech Publications, 2014. – T. 682. – C. 246-250.
[4]   Begljakov V. Y., Timofeev V. Y., Dokhnenko M. V. Parameters of Force Interaction of Elements the Wave Transmission with Intermediate Rolling Bodies in Geokhd's Transmission //Applied Mechanics and Materials. – Trans Tech Publications, 2014. – T. 682. – C. 282-287.
[5]   Aksenov, Vladimir V., Mikhail Yu Blaschuk, and Mikhail V. Dubrovskii. "Estimation of torque variation of geohod transmission with hydraulic drive." Applied Mechanics and Materials. Vol. 379. 2013.
[6]   Efremenkov, Andrey Borisovich, V. V. Aksenov, and M. Yu Yurga. "Force parameters of geohod transmission with hydraulic drive in various movement phases." Strategic Technology (IFOST), 2012 7th International Forum on. IEEE, 2012.
[7]   Sadovets, V. Yu, V. Yu Beglyakov, and V. V. Aksenov. "Development of math model of geokhod bladed working body interaction with geo-environment." IOP Conference Series: Materials Science and Engineering. Vol. 91. No. 1. IOP Publishing, 2015.
[8]   Aksenov, Vladimir V., Andrey Borisovich Efremenkov, and V. Yu Begljakov. "The influence of relative distance between ledges on the stress-strain state of the rock at a face." Applied mechanics and materials. Vol. 379. 2013.
[9]   Chernukhin, R. V., A. A. Dronov, and M. Y. Blashchuk. "The application of the analytic hierarchy process when choosing layout schemes for a geokhod pumping station." IOP Conference Series: Materials Science and Engineering. Vol. 91. No. 1. IOP Publishing, 2015.
[10]   Walter, A. V., and V. V. Aksenov. "Determining deviations in geometry of the geokhod shells." Applied Mechanics and Materials. Vol. 770. 2015.