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FINITE ELEMENT MODEL OF THE ORE DISINTEGRATION PROCESS - PART 2

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ABSTRACT:
This article is focused on the numerical analysis of the hard rock (ore) disintegration process (continuation of the firstly article published in this Journal, see [3]). The bit moves and sinks into the hard rock (mechanical contact with friction between the ore and the cutting bit) and subsequently disintegrates it. The disintegration (i.e. stress-strain relationship, contact forces, reaction forces and fracture of the ore) is solved via FEM (MSC.MARC/MENTAT software) and SBRA (Simulation-Based Reliability Assessment) method (Monte Carlo simulations, Anthill and Mathcad software). Disintegration of the ore is done by deactivation of the finite elements which satisfy conditions of fracture. Material of the ore (i.e. yield stress, fracture limit, Young's modulus and Poisson's ratio) are given by bounded histograms (i.e. stochastic inputs which describe better the reality). The results (reaction forces in the cutting bit) are also of stochastic quantity and they are compared with experiment. Application of SBRA method at this area is a new and modern trend. However, to solve this problem (material and structural nonlinearities, the large number of elements, many iteration steps and many Monte Carlo simulations) takes long time. Hence, parallel computers were used to solve the large computational needs of this problem.
KEYWORDS:
Hard rock (ore), cutting bit, disintegration process, FEM, SBRA method, parallel computing

1. INTRODUCTIVE NOTES

Provision of sufficient quantities of raw materials and energy for the processing industry is one of the limiting factors of further development. Hence, it is important to understand the analysis of the ore disintegration process, which includes the analysis of the bit (i.e. excavation tool) used in mining operations. The main focus is dedicated to the modelling of the mechanical contact between the bit and the ore and following disintegration of the ore see references [2] and [3].

This new article is a continuation of the first article published in this Journal, see [3].

2. FINITE ELEMENT MODEL OF THE ORE DISINTEGRATION PROCESS

FEM (i.e. MSC.MARC/MENTAT 2005r3 and 2008r1 software) was used in the solution of the ore disintegration process. Figure 1 shows the basic scheme (plain strain formulation, mechanical contact with friction between the bit and platinum ore, boundary conditions, etc.).

From Fig.1, it is evident that the bit is moving into the ore by the prescribed time dependent function $u = f(t)$, and subsequently disintegrate it. When the bit is moving into the ore (i.e. a mechanical contact between the bit and the ore occurs) the stresses σ_{HMH} (i.e. equivalent von Mises stresses) in the ore increases. When the situation $\sigma_{\mathrm{HMH}} > \mathrm{R_m}$ occurs (i.e. equivalent stress is greater than the fracture limit) in some elements of the ore, then these elements break off (i.e. these elements are dead). Hence, the disintegration of a part of the ore is done. In the MSC.MARC/MENTAT software, it is done by deactivating the elements which satisfy condition $\sigma_{\mathrm{HMH}} > \mathrm{R_m}$. This deactivation of the elements was done in every 5th step of the solution. For more information see references [2] and [3].

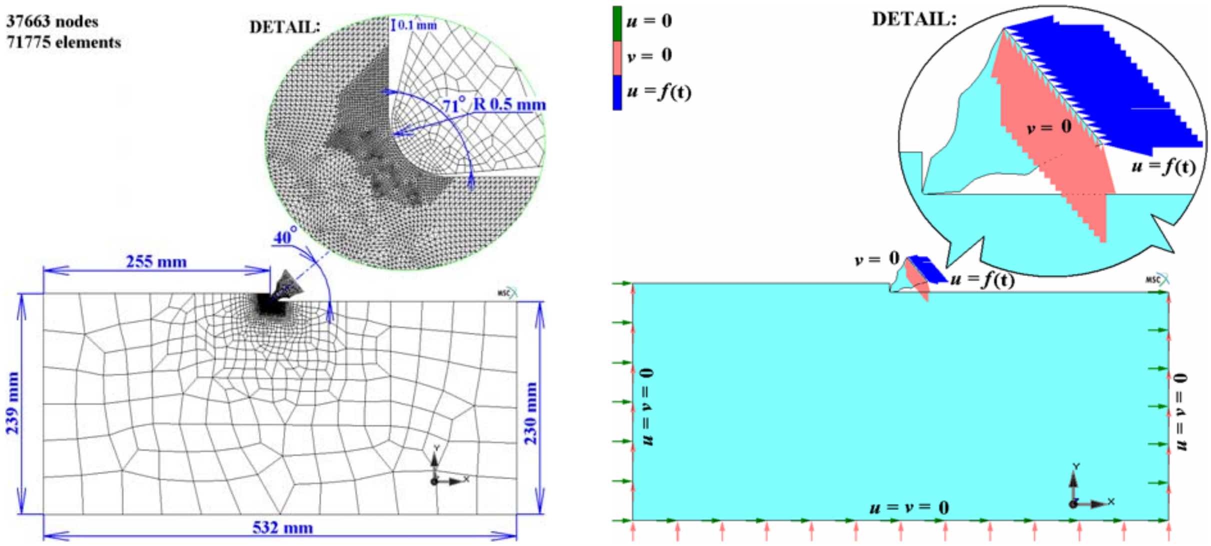
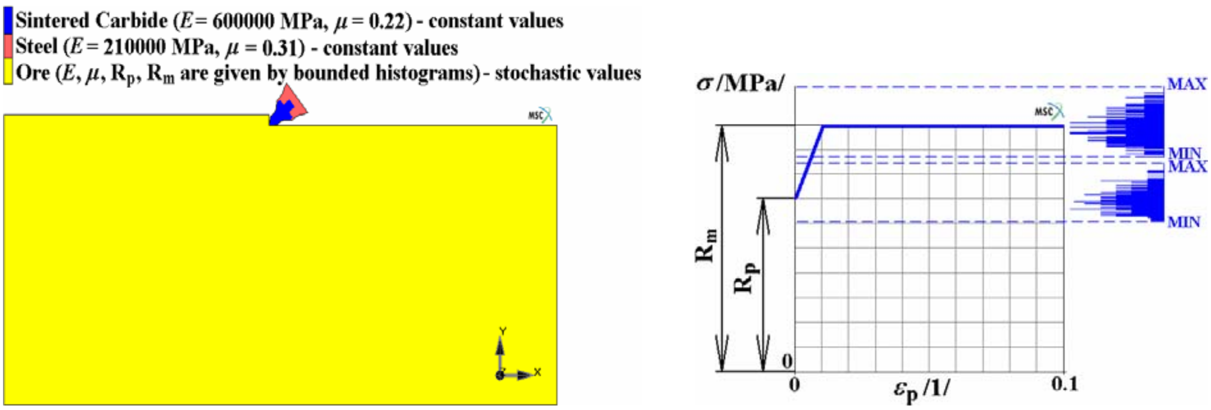


Figure 1. Geometry of the 2d fe model, boundary conditions and its details.

3. PROBABILISTIC INPUTS - SIMULATION-BASED RELIABILITY ASSESSMENT METHOD

Deterministic approach (i.e. all type of loading, dimensions and material parameters etc. are constant) is the elder but simple way how to get the solution of mechanical systems. However, the deterministic approach cannot truly include variability of all inputs, because the real nature and the world are stochastic. Solution of the ore disintegration process via deterministic approach is shown in references [2] and [3]. But this problem is also solved via probabilistic approach which is based on the statistics.



a) whole model b) material of the ore (stress σ vs. plastic strain ε_p).

Figure 2. Material properties

Let's consider probabilistic approach "Simulation-Based Reliability Assessment" (SBRA) Method (i.e. all inputs are given by bounded histograms which include the real variability of inputs). Application of SBRA method (based on the Monte Carlo simulations) is the modern and new trend in mechanics; see for example references [1], [4] and [5].

Material properties (i.e. isotropic and homogeneous materials) of the whole system are described in Fig.2, where E is Young's modulus of elasticity and μ is Poisson's ratio.

Hence, the bit is made of sintered carbide (sharp edge) and steel. The ore material is elasto-plastic with yield limit $R_p = 9.946^{+1.722}_{-0.911}$ MPa and fracture limit $R_m = 12.661^{+0.925}_{-0.650}$ MPa, which are given by bounded histograms see Fig.2 and 3.

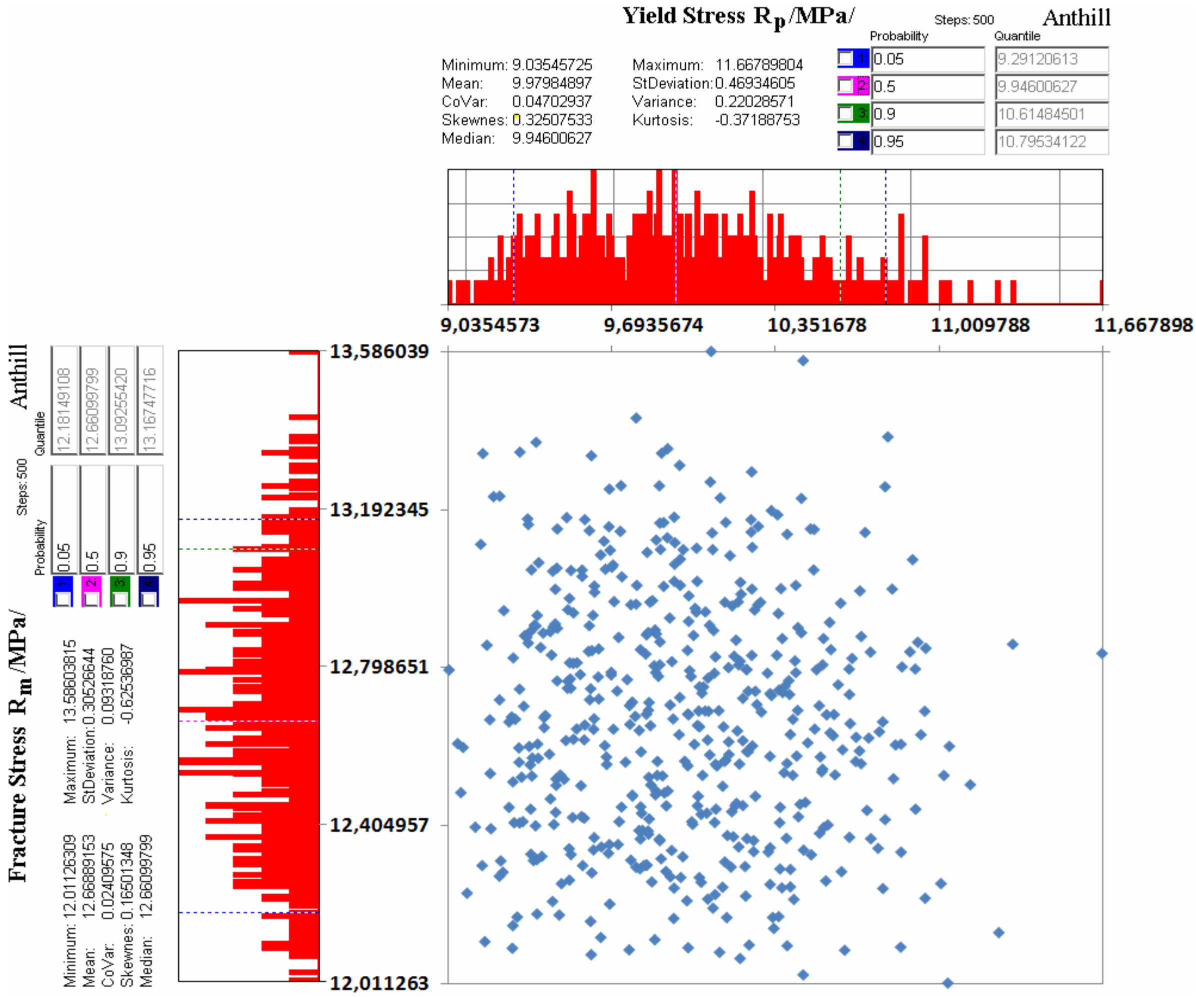


Figure 3. Stochastic inputs for material of the ore (histograms for yield stress and fracture stress, results of anthill software).

Elastic properties of the ore are described by Hooke's law by given histograms ($E = 18513.8^{+2608.8}_{-2418.8}$ MPa and $\mu = 0.199^{+0.021}_{-0.019}$), see Fig.4 and 5.

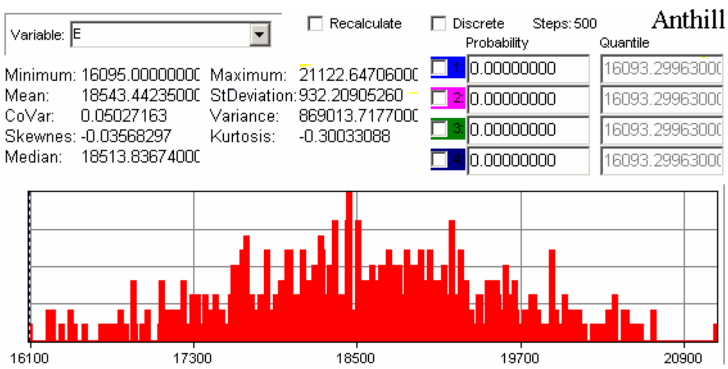


Figure 4. Stochastic inputs for material of the ore (histogram of young's modulus, result of anthill software).

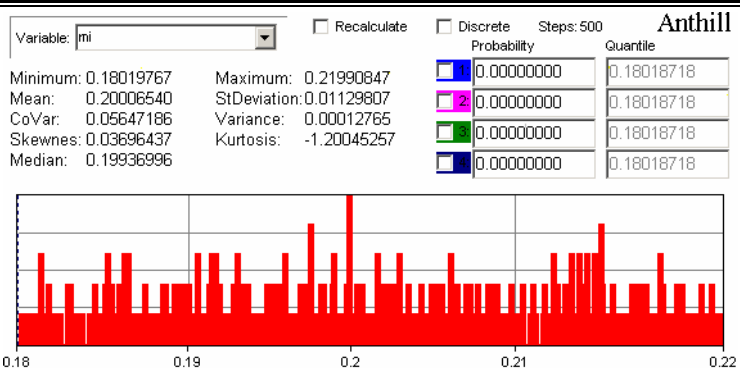


Figure 5. Stochastic inputs for material of the ore (histogram of poisson's ratio, result of anthill software)

Application of SBRA method in combination with FEM and subsequent evaluation of the results are shown in Fig.6. Hence, Anthill, MSC.Marc/Mentat and Mathcad software were used.

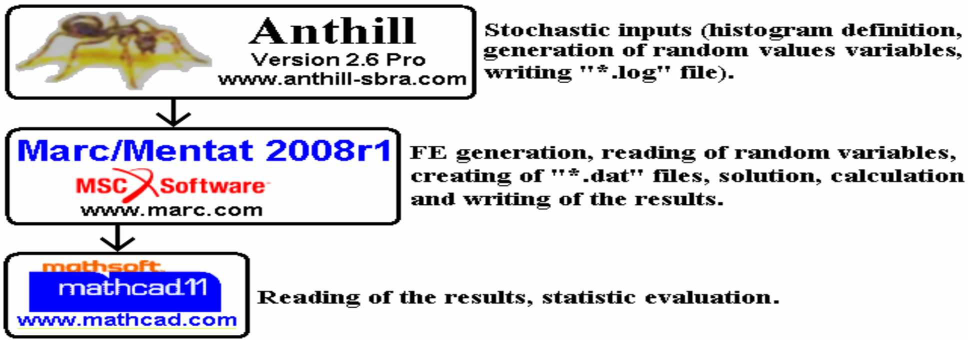


Figure 6. Computational procedure - application of sbra method (solution of the ore dissintegration process.

4. SOLUTION - SBRA METHOD IN COMBINATION WITH FEM

Table 1. Used parallel computers

COMPUTER NAME:	COMPUTER DESCRIPTION:	SOFTWARE	no. of CPU:	no. of MC simulations	Wall time /hours/:
ALFA:	Linux OS, 8 NODES. NODE CONFIGURATION: 2 X CPU AMD Opteron 250 (FREQUENCY 2.4 Ghz, 1MB L2 Cache) WITH 4 GB RAM (400mhz DDR)	MSC.Marc/ Mentat	16	312	70.395
OPTERON:	Linux OS, 1 NODES. NODE CONFIGURATION: 2 X CPU AMD Opteron 248 (FREQUENCY 2.2 Ghz) WITH 8 GB RAM	MSC.Marc/ Mentat	2	28	54.6
QUAD:	Linux OS, 4 NODES. NODE CONFIGURATION: 1 X CPU AMD Opteron 848 (FREQUENCY 2.2 Ghz) WITH 4 GB RAM	MSC.Marc/ Mentat	4	86	69.015
pcA632d:	MS WINDOWS XP PROFESSIONAL 64 BIT OS, 4 NODES, CONFIGURATION: INTEL CORE 2 QUAD CPU Q9300 (FREQUENCY 2.5 Ghz) WITH 8 GB RAM	MSC.Marc/ Mentat, ANTHILL, MATHCAD	4	74	68.82
				Σ 500	

Because of the material non-linearities, the mechanical contacts with friction, the large number of elements, many iteration steps and chosen 500 Monte Carlo simulations, four parallel computers were used to solve the large computational needs of this problem, see Tab.1.

Hence, Domain Decomposition Method (i.e. application of parallel computers) was used, see Fig.7.

The whole solved time of the non-linear solution (i.e. 1.04 s) was divided into 370 steps of variable length. The Full Newton-Raphson method was used for solving the non-linear problem.

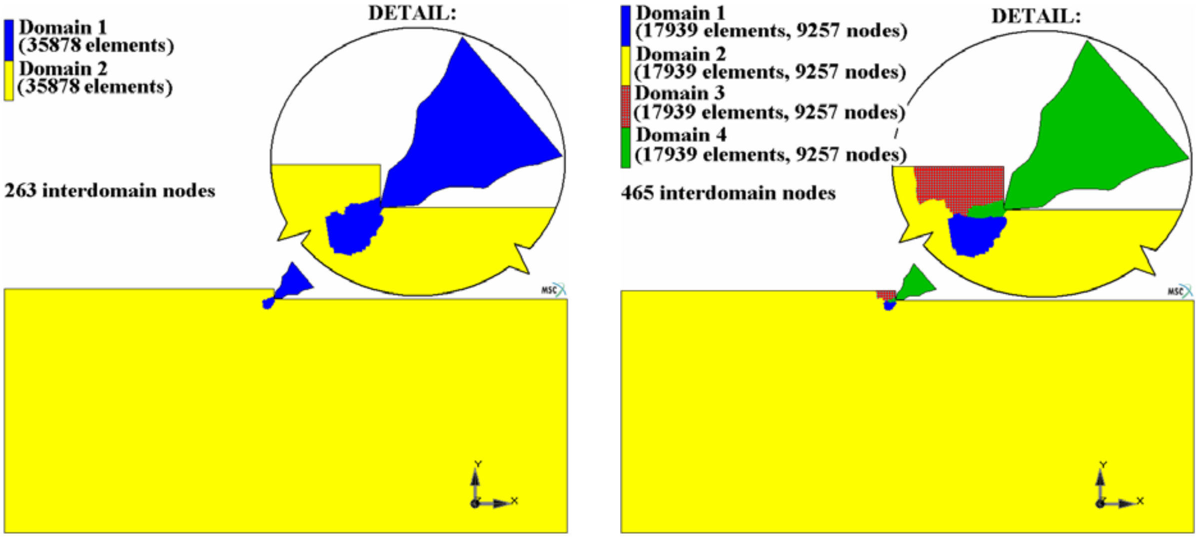


Figure 7. Domain decomposition method used for application of 2×cpu and 4×cpu

Hence, from the Tab.1 it is evident that the time of the solution of 500 Monte Carlo simulations (calculated contemporaneously on four different parallel computers) takes cca 70 hours.

5. RESULTS - STOCHASTIC EVALUATION

The following figures 8 to 11 show equivalent stress (i.e. σ_{HMH} distributions) at some chosen time t of the solution calculated for 1 of 500 Monte Carlo simulations (i.e. for one situation when the material of the ore is described by values $R_p = 12$ MPa, $R_m = 13.5$ MPa, $E = 20000$ MPa and $\mu = 0.2$). Moving of the bit and also the subsequent disintegration of the ore caused by the cutting bit is evident.

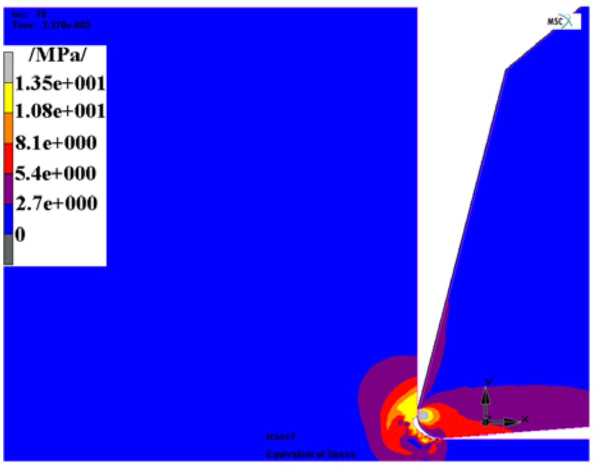


FIGURE 8. - t = 3.37×10^{-2} s (FEM results)

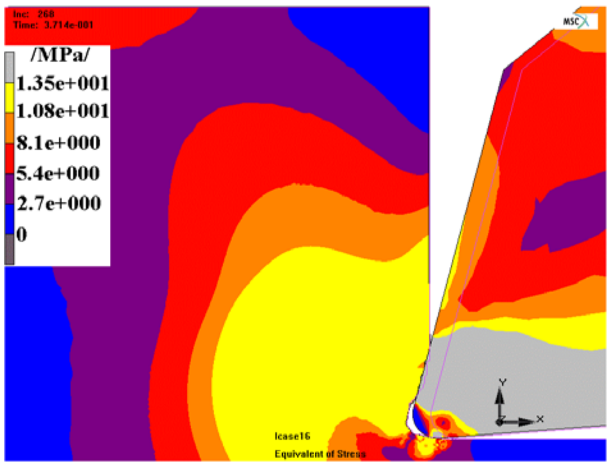
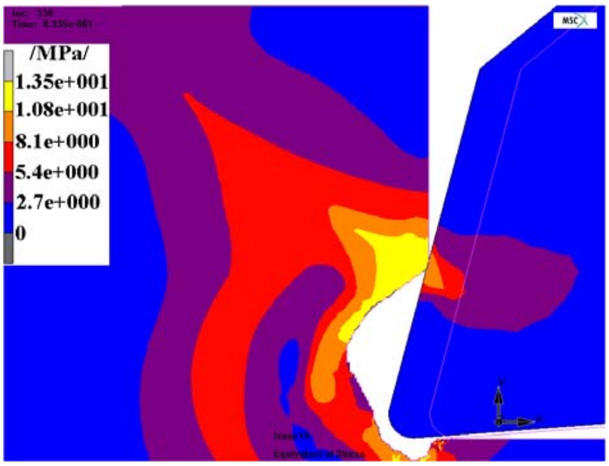


FIGURE 9. - t = 3.714×10^{-1} s (FEM results)



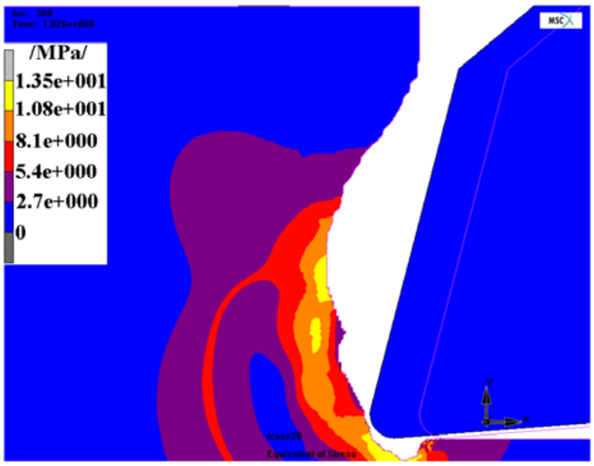


FIGURE 10. - t = 8.335×10^{-1} s (FEM results) FIGURE 11. - t = 1.026 s (FEM results)

From the results of FEM the reaction forces R_X, R_Y and total reaction force $R=\sqrt{R_X^2+R_Y^2}$ which act in the bit, can be calculated, see Fig.12 (for one simulation, i.e. for the situation when the material of the ore is described by values $R_p = 12\ \text{MPa}$, $R_m = 13.5\ \text{MPa}$, $E = 20000\ \text{MPa}$ and $\mu = 0.2$).

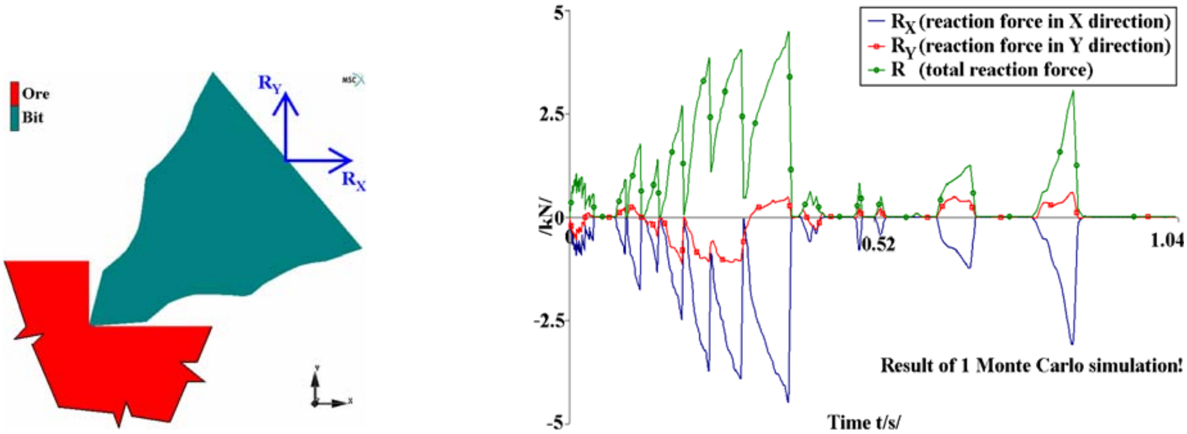


Figure 12. Reaction forces in the bit (fem results)

Histogram of total reaction forces acquired from 500 simulations is shown in Fig.13.

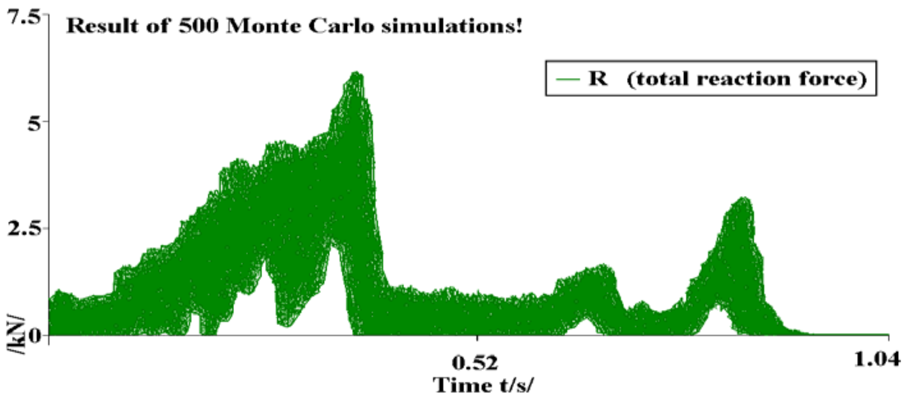


Figure 13. Total reaction forces in the bit (FEM results)

Maximum total reaction force (acquired from 500 Monte Carlo simulation) is given by histogram $R_{MAX_{FEM}} = 5068^{+1098}_{-984}\ \text{N}$, see Fig.14.

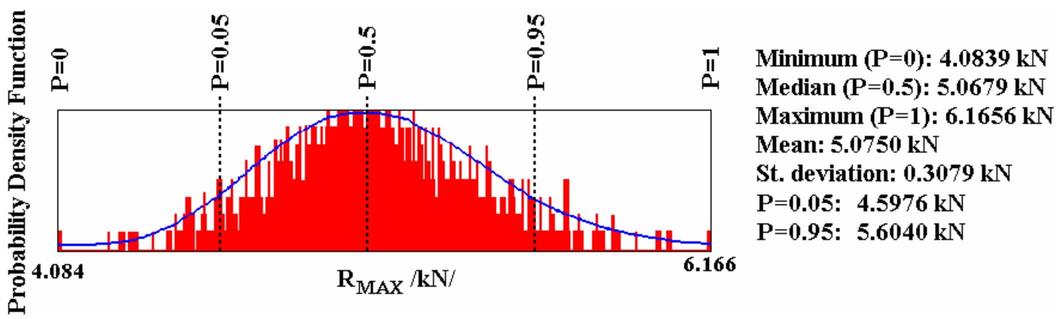


Figure 14. Maximum total reaction forces in the bit (FEM results) and its evaluation.

6. COMPARSION OF STOCHASTIC RESULTS WITH EXPERIMENTAL MEASUREMENTS

The calculated maximum forces (i.e. FEM solutions, see Fig.14) can be compared with the experimental measurements (i.e. compared with the part of Fig.15), see also [2] and [3].

From the evaluation of one force measurement (Fig.15) is evident that the maximum force is $R_{MAX_{EXP}} = 5280\ \mathrm{N}$. Hence, the relative error calculated for acquired median value $R_{MAX_{SBRA,\,FEM-MED}} = 5068\ \mathrm{N}$, see Fig.14, are:

$$\Delta_{R_{MAX}} = 100 \times \frac{R_{MAX_{EXP}} - R_{MAX_{SBRA,\,FEM-MED}}}{R_{MAX_{EXP}}} = 100 \times \frac{5280 - 5068}{5280} = 4.02\ \%. \qquad (1)$$

The error of 4.02% is acceptable. However, the experiments also have a large variability of results caused by anisotropic and stochastic properties of the material and by the large variability of reaction forces, for example see Fig.15.

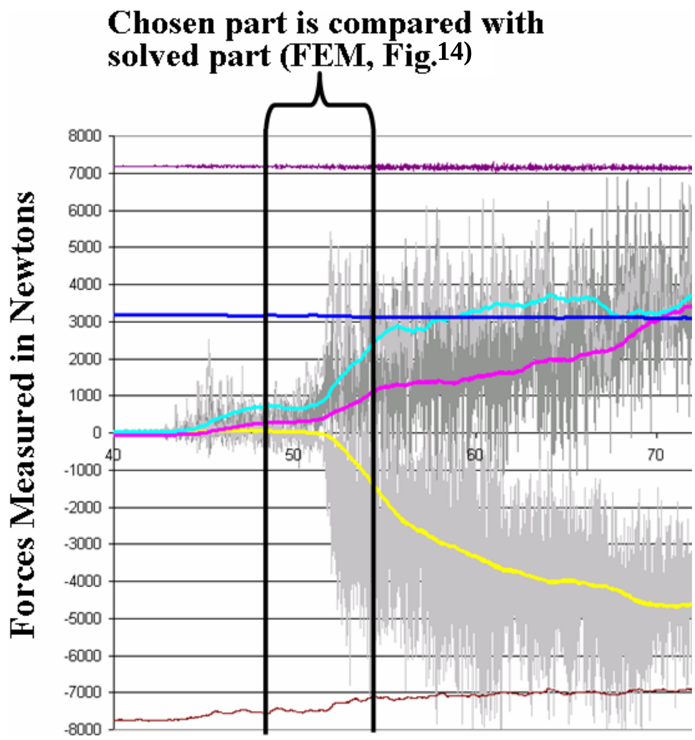


Figure 15. Experimental measurements and its comparison with the fem solution

5. THE CONCLUSIONS

This contribution shows combination of SBRA (Simulation Based Reliability Assessment) Method and FEM as suitable tool for the solution of the hard rock (ore) disintegration process. All basic aspects (i.e. 2D boundary conditions, material nonlinearities, mechanical contacts and friction between the cutting bit and the ore, methodology of deactivation of FE elements during the ore disintegration process, application of parallel computers) was explained. Using of deactivating of FE elements during the ore disintegration process (as a way of crack expansion) is a new and modern way of solution of this type of problems.

The error of the SBRA-FEM results (i.e. comparing with experiments, see eq. (1)) is acceptable. Hence, SBRA and FEM can be useful tool for the solution of the ore disintegration process.

Because the real material of the ore (i.e. yield limit, fracture limit, Young's modulus, Poisson's ratio etc.) has large variability, the stochastic theory and theory of probability was applied (i.e. application of SBRA Method).

SBRA Method, which is based on Monte Carlo simulations, can include all stochastic inputs and then all results are also of stochastic quantity. However, for better application of SBRA method (for the solution of this large problem of mechanics) must be used superfast parallel computers. Instead of 500 Monte Carlo simulations (wall time cca 70 hours, presented in this article) must be calculated $>10^4$ simulations (wall time cca 58 days). However, in our department, it will be possible to solve it when faster parallel computers should be available.

All presented results were applied for optimisation and new design of the bit.

In the future will be applied 3D FE models (instead of 2D plane strain formulation), which can be more accurate. Other methods for the solution of ore disintegration process are presented in [6] and [7].

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