NUMERICAL SOLUTION OF HARD ROCK DISINTEGRATION PROCESS

NUMERICKÉ ŘEŠENÍ PROCESU ROZPOJOVÁNÍ TVRDÝCH HORNIN

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Abstract

This paper is focused on a numerical analysis of the hard rock (ore) disintegration process. There is discussed the possibility of using computational modelling for the mechanical contact problem between the hard rock and a cutting bit. The bit (i.e. an excavation tool with a flat frontal side and a conical edge) moves and sinks into the hard rock and subsequently disintegrates it. The whole problem of the hard rock disintegration process (i.e. stress-strain relationship, contact forces, reaction forces and fracture of the ore) is solved via Finite Element Method (MSC.MARC/MENTAT software). The rock disintegration process was solved via deactivation of finite elements which satisfy conditions of fracture. Some results (i.e. reaction forces in the cutting bit) are also compared with experimental measurements.

Abstrakt

Tento článek je zaměřen na numerickou analýzu rozpojování tvrdých hornin (rud). Je rozebírán problém možností počítačového modelování problematiky mechanického kontaktu mezi tvrdou horninou a řezným nástrojem. Nůž (tj. rozpojovací nástroj s plochým čelem a kuželovým břitem) se pohybuje a vniká do tvrdé horniny a následně ji rozpojuje. Celá problematika rozpojování tvrdých hornin (tj. napěťově-deformační stav, kontaktní síly, reakční síly a lom rudy) je řešená pomocí Metody konečných prvků (MSC.MARC/MENTAT software). Proces rozpojování hornin je řešen pomocí deaktivace elementů, které splňují podmínky lomu. Některé výsledky (tj. reakční síly v řezném nástroji) jsou také porovnány s experimentálními měřeními.

Key words: rock mechanics, hard rock, disintegration process, FEM, mechanical contact, nonlinearities

1 INTRODUCTION

Scientific and technical development, in all areas of the world-wide industry, is described by growing demand for basic resources of raw materials and energy. Provision of sufficient quantities of raw materials and energy for the processing industry is the main limiting factor of further development.

In this case, it is very important to understand the analysis of the ore disintegration process, which includes the analysis of a 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, see Fig.1 and references [1] to [6].

Fig. 1 Typical Example of Mechanical Interaction between Bits and Hard Rock (i.e. Ore Disintegration Process, Experimental Measurements).

Scientific and technical development provides new ways for the solution of the ore disintegration process. There is also a possibility of Finite Element Method (FEM) applications. Hence, FEM (i.e. MSC.MARC/MENTAT 2005r3 software, see reference [7]) was used in solution of the ore disintegration process.

2 FINITE ELEMENT MODEL OF THE ORE DISINTEGRATION PROCESS

Figures 2 and 3 show the basic scheme of the solution via FEM. The FE mesh contains 37663 nodes and 71755 plane elements.

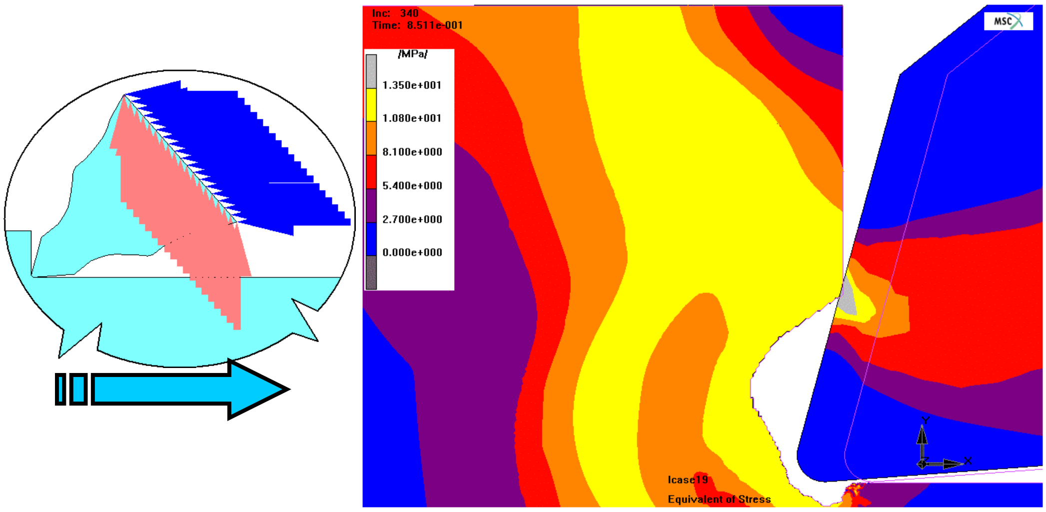

Fig. 2 Basic Scheme of the Ore Disintegration Process Solved via FEM Software MSC.MARC/MENTAT 2005r3.

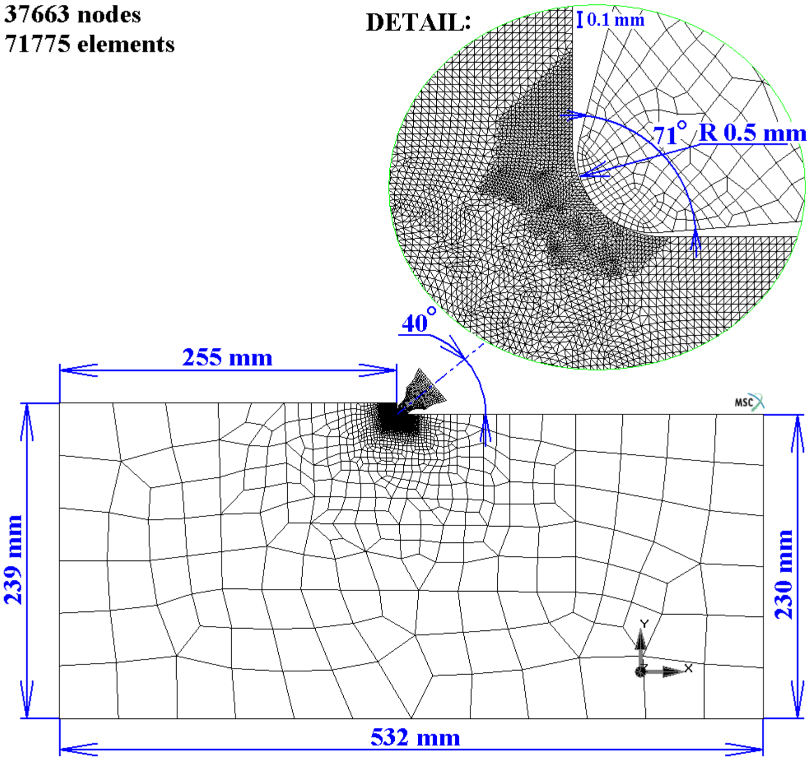

Fig. 3 Scheme and Geometry of the 2D FE Mesh Model and its Detail.

The basic boundary conditions for plain strain formulation and loads are described in Fig.4, where u is the prescribed X-axis displacement and v is the prescribed Y-axis displacement. From Fig.4 it is evident that the bit is moving into the ore by the prescribed time dependent function $u = f(t)$, see arrows in Fig.4. There is a prescribed zero displacement on three edges of the modelled area, see arrows in Fig.4.

There is also a mechanical contact with Coulomb's friction between the bit and platinum ore, because the bit works through the ore and disintegrate it, see Fig.5.

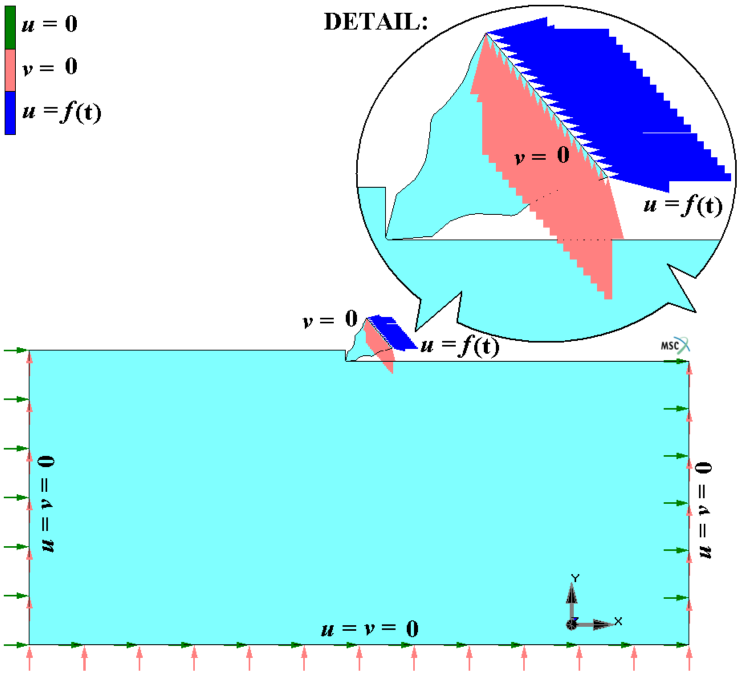

Fig. 4 Boundary Conditions Scheme of the 2D Model (Plane Strain Formulation).

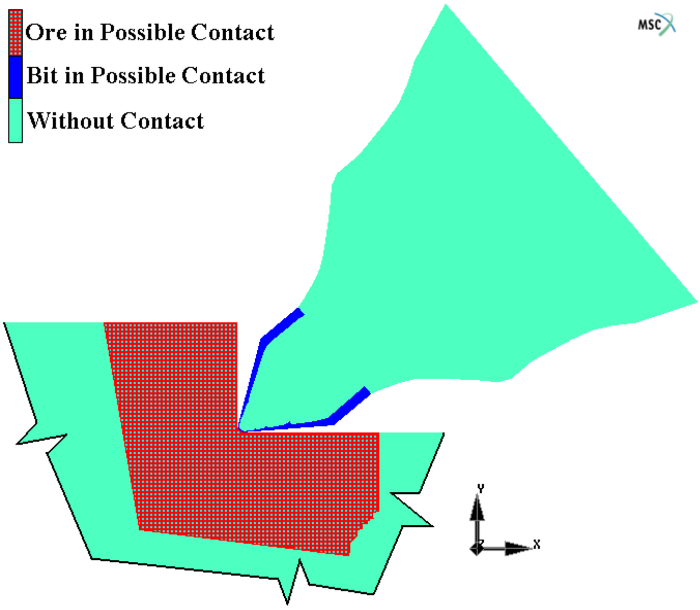

Fig. 5 Boundary Conditions (Mechanical Contacts).

Material properties (i.e. isotropic and homogeneous materials) of the whole system are illustrated in Fig.6, 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 a yield limit $\mathrm{R_p} = 12\ \mathrm{MPa}$ and fracture limit $\mathrm{R_m} = 13.5\ \mathrm{MPa}$, see Fig.7.

When the bit is moving into the ore (i.e. a mechanical contact between the bit and the ore occurs) the stresses (i.e. equivalent von Mises stresses, see reference [8]): $\sigma_{\mathrm{HMH}} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_3\sigma_1}$ in the ore increases. When the situation $\sigma_{\mathrm{HMH}} \geq \mathrm{R}_{\mathrm{m}}$ 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 occurs. In the MSC.MARC/MENTAT software, it happens by deactivating the elements which satisfy condition $\sigma_{\mathrm{HMH}} \geq \mathrm{R}_{\mathrm{m}}$. This deactivation of elements was checked and done in every 5th. step of the solution.

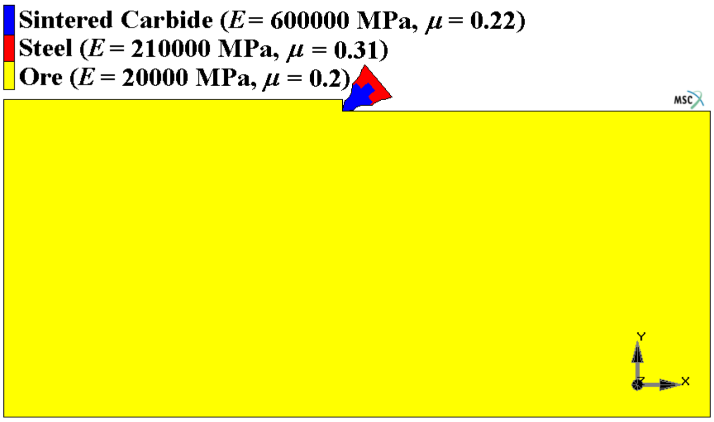

Fig. 6 Material Properties.

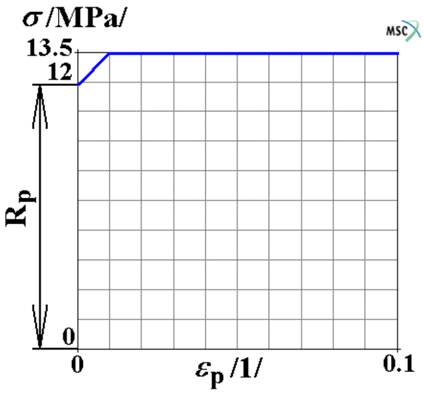

Fig. 7 Relationship between Stress and Plastic Strain for Platinum Ore.

3 NUMERICAL SOLUTIONS

Because of material non-linearities, the mechanical contacts with friction, the large number of elements and many iteration steps, four parallel computers (Linux OS, 4×CPU AMD Opteron 848 with 4 GB RAM memory, Domain Decomposition Method, FETI procedure), were used to solve the large computational needs of this problem, see Fig.8.

The whole 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.

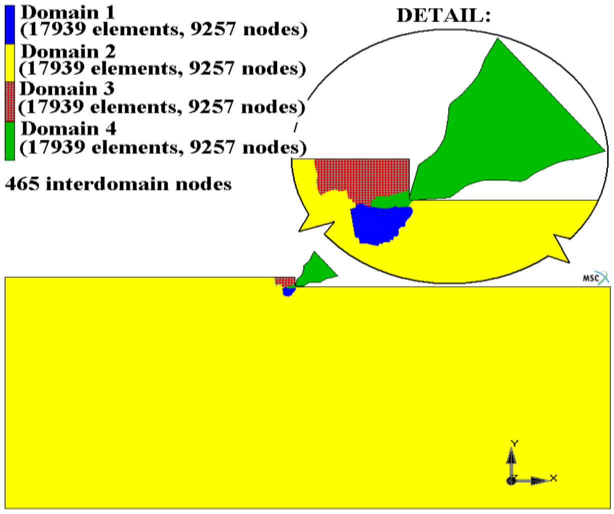

Fig. 8 Domain decomposition method applied for 4×cpu.

4 RESULTS OF FEM

The following figures show equivalent stress (i.e. σ_{HMH} distributions) at some chosen time t of the solution. Hence: Fig.9 - t =0 s, i.e. start of the solution, Fig.10 - t =1.639×10^{-2} s, Fig.11 - t = 3.37×10^{-2} s, Fig.12 - t = 8.047×10^{-1} s, Fig.13 - t = 1.928×10^{-1} s, Fig.14 - t = 2.388×10^{-1} s, Fig.15 - t = 3.714×10^{-1} s, Fig.16 - t = 5.796×10^{-1} s, Fig.17 - t = 8.335×10^{-1} s, Fig.18 - t = 8.511×10^{-1} s and Fig.19 - t = 1.026×10^{-1} s.

In Figures 9 to 19, the moving of the bit is evident and also the subsequent disintegration of the ore caused by the cutting bit.

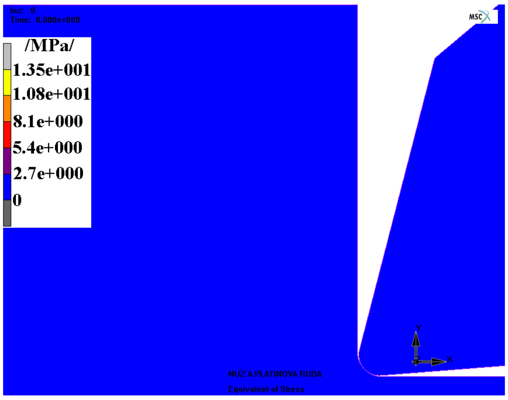

Fig.9 - t =0 s (Start of the Solution).

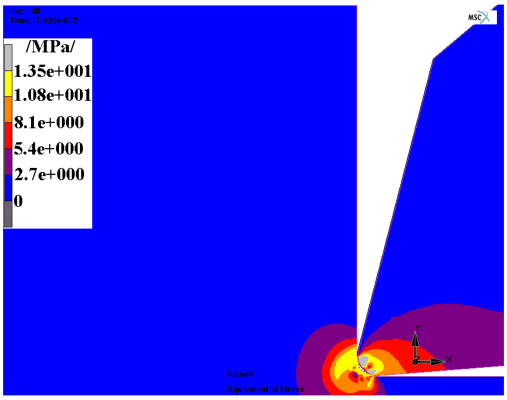

Fig. 10 - t =0.01639 s.

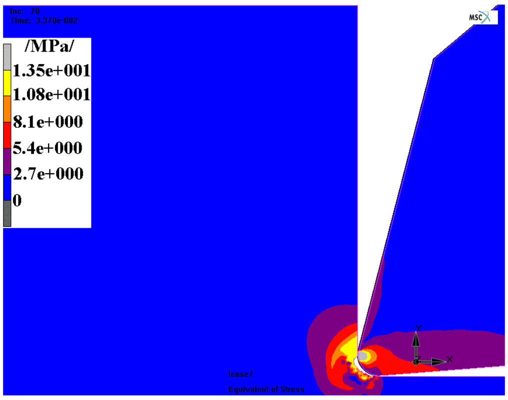

Fig. 11 - t = 0.0337 s.

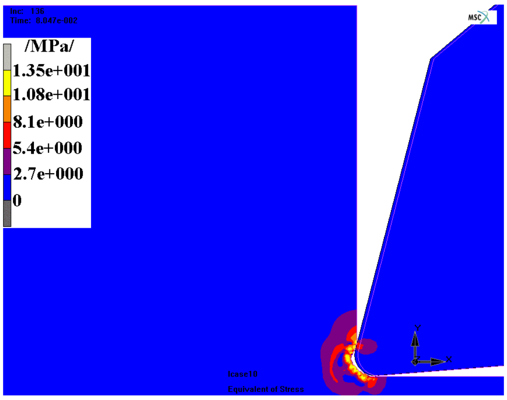

Fig. 12 - t = 0.08047 s.

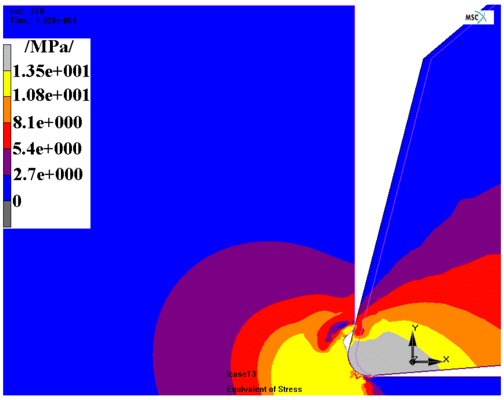

Fig. 13 - t = 0.1928 s.

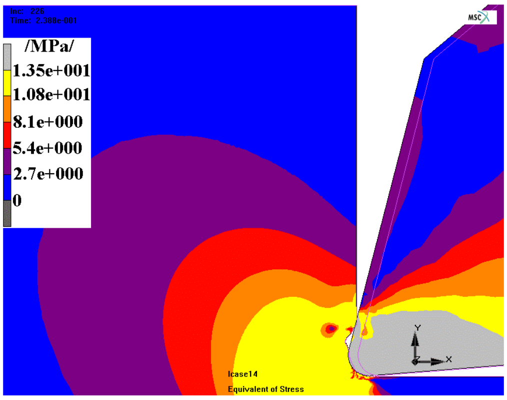

Fig. 14 - t = 0.2388 s.

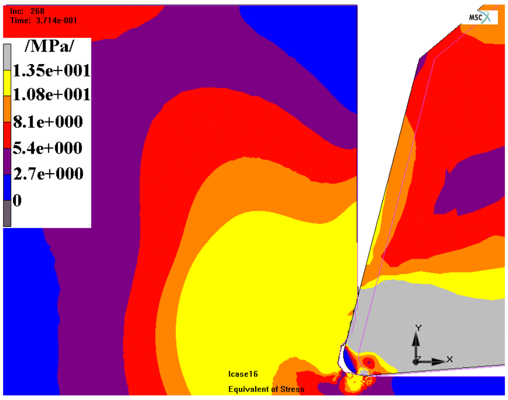

Fig. 15 - t = 0.3714 s.

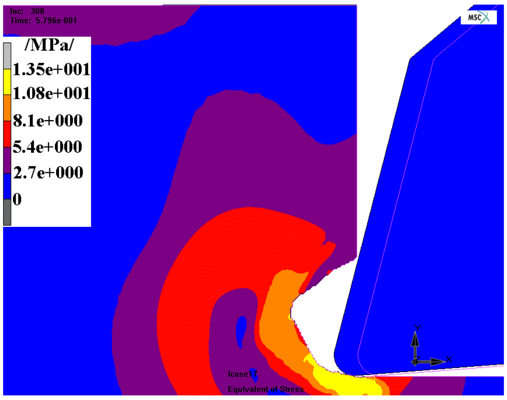

Fig. 16 - t = 0.5796 s.

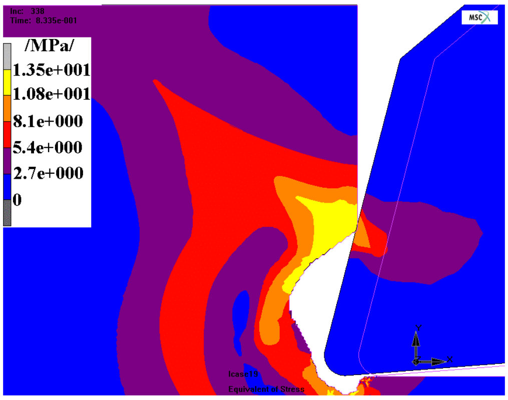

Fig.17 - t = 0.8335 s.

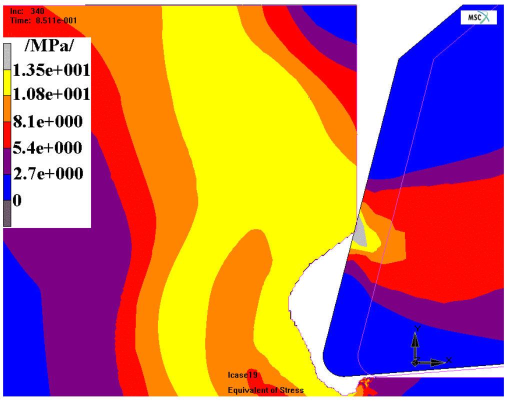

Fig.18 - t = 0.8511 s.

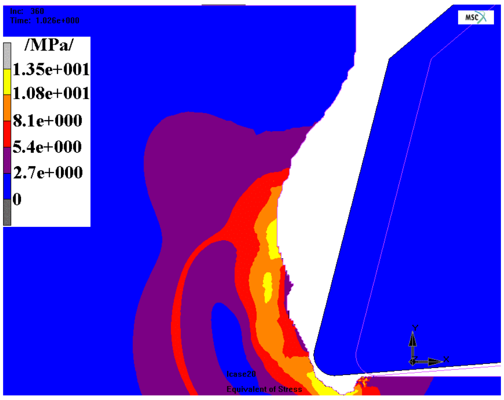

Fig. 19 - t = 1.026 s.

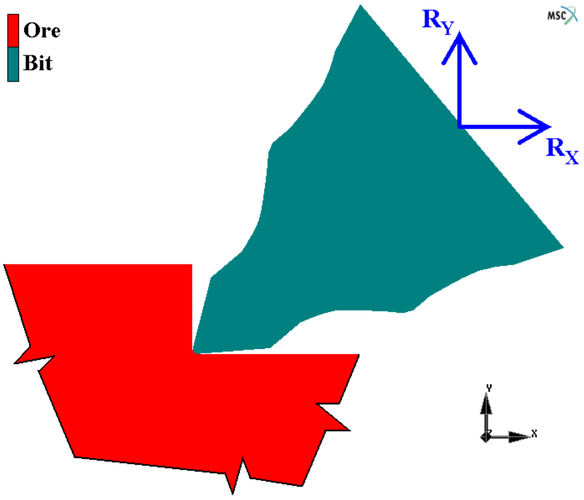

Fig. 20 Reaction Forces in the Bit.

From the results of FEM the reaction forces R_X, R_Y and total reaction force $R = \sqrt{R_X^2 + R_Y^2}$ acting in the bit, can be calculated, see Figs. 20 and 21. The maximum reaction force (acquired by FEM) is $R_{MAX_{FEM}} = 4598\ \text{N}$.

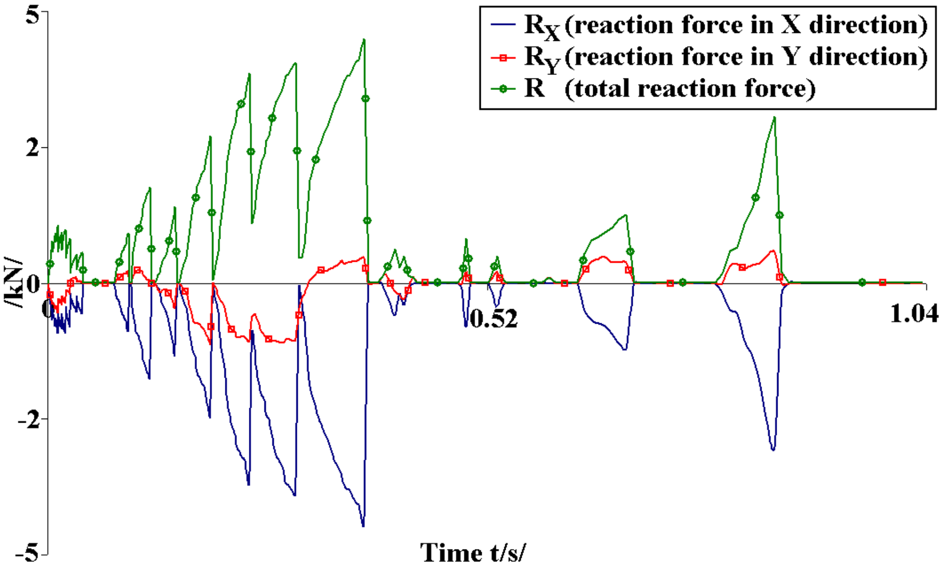

Fig. 21 Reaction Forces in the Bit.

5 COMPARSION OF FEM RESULTS WITH EXPERIMENTAL MEASUREMENTS

The calculated forces (i.e. FEM solution, see Fig.21) can be compared with the experimental measurements (i.e. compared with the part of Fig.22, i.e. the record of reaction forces).

From the evaluation of experiments it is evident that the maximum force is $R_{MAX_{EXP}} = 5280\ \mathrm{N}$. Hence, the relative error is:

$$\Delta_{R_{MAX}} = 100 \times \frac{R_{MAX_{EXP}} - R_{MAX_{FEM}}}{R_{MAX_{EXP}}} = 12.9\,\%. \quad (1)$$

The error of 12.9% is caused by the chosen 2D FE model (i.e. plane strain formulation) which is sometime a pure (but simple) approximation of real 3D situation. However, the experiments also have a large variability of inputs caused by anisotropic and stochastic properties of the material and by the large variability of reaction forces, for example see Fig.22.

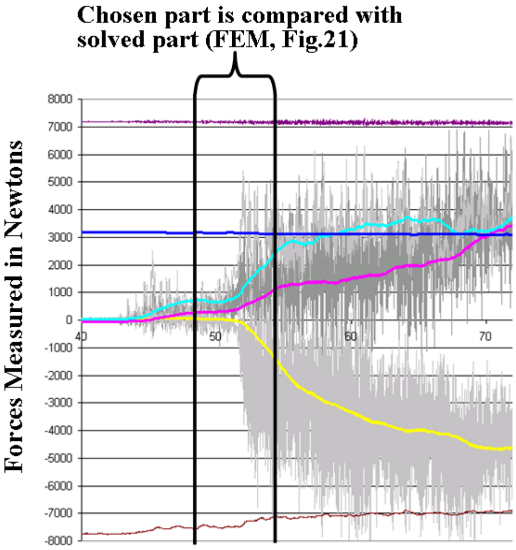

Fig. 22 Experimental Measurements and its Comparison with the FE Solution.

6 CONCLUSIONS

The error of the FEM result (i.e. comparing with experiments, see eq. (1)) is acceptable. Hence, FEM can be useful tool for the solution of the ore disintegration process. All results were applied to an optimization and a new design of the bit.

The whole disintegration process (i.e. the bit moves and sinks into the ore) was solved in a new and modern way (i.e. by deactivating the elements which satisfy condition of fracture).

In the future 3D FE models (instead of 2D plane strain formulation) will be applied, which can be more accurate.

Since the 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 can be applied. Hence, in the future, the whole presented problem can be solved via Simulation-Based Reliability Assessment (SBRA) Method, see references [9] to [11]. The SBRA Method, which is based on Monte Carlo simulations, can include all stochastic (real) inputs and then all results are also of a stochastic (real) quantity.

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RESUMÉ

Vědecko/technický rozvoj nabízí nové cesty řešení velmi složité problematiky rozpojování hornin. Proto je, jako jedné z možných cest, vhodné také využití Metody konečných prvků (MKP). Tento článek je zaměřen na numerickou analýzu rozpojování tvrdých hornin (rud). Je rozebírán problém možností počítačového modelování problematiky mechanického kontaktu se třením mezi poměrně tvrdou horninou (platinová ruda) a řezným nástrojem - nožem (slinutý karbid a ocel). Nůž (tj. rozpojovací nástroj s plochým čelem a kuželovým břitem) se pohybuje a vniká do tvrdé horniny a po překonání meze kluzu horniny ji následně rozpojuje. Celá problematika rozpojování tvrdých hornin (tj. napěťově-deformační stavy, kontaktní síly, mechanický kontakt se třením, reakční síly, elasto-plastický materiál rudy a lom rudy) je řešená pomocí Metody konečných prvků

(MSC.MARC/MENTAT software). Vlastní rozpojování rudy je řešeno novým a moderním způsobem pomocí deaktivace (tj. postupného vyřazování) konečných prvků jejichž napjatost překročila mez pevnosti materiálu rudy. Z prezentovaných výsledků je zřetelné postupné odlamování rudy. Při vlastním výpočtu bylo využito kombinace víceprocesorových počítačů (4× CPU), který při paralelním řešení využil metodu FETI doménové dekompozice. Aplikace superpočítače měla za následek snížení výpočtového času. Některé výsledky (reakční síly v noži) jsou také porovnány s experimentálními měřeními, přičemž vypočtená relativní chyba je 12.9%, což je (vzhledem k velkému rozptylu naměřených dat) přijatelné. Prozatím byla řešena jen úloha rovinné deformace, přičemž v budoucnu se také plánuje řešení mnohem složitější (reálné) prostorové úlohy. Slibné je také do budoucna využití pravděpodobnostních přístupů „Simulation-Based Reliability Method“ (SBRA), která umožňuje respektovat také reálný vliv náhodných parametrů hornin (modul pružnosti, Poissonovo číslo, mez kluzu, mez pevnosti atp.), ale i nože (modul pružnosti, otupení nože v průběhu rozpojování atp.). Metoda SBRA je založena na simulacích Metody Monte Carlo a vzhledem k velké složitosti a náročnosti (velký počet elementů, materiálové nelinearity, mechanický kontakt se třením) je její aplikace při řešení této úlohy v ČR otázkou blízké budoucnosti. Pro řešení velkých nelineárních úloh metodou SBRA je třeba využít výkonné více-procesorové superpočítače.