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ПРИМЕНЕНИЕ НЕЛОКАЛЬНОЙ МОДЕЛИ НЕУПРУГИХ ДЕФОРМАЦИЙ В ДИНАМИЧЕСКОЙ ЗАДАЧЕ РАЗРУШЕНИЯ ГОРНОЙ ПОРОДЫ

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При бурении скважин режуще-скалывающими долотами основным фактором является динамическое взаимодействие резца и горной породы. В данной работе изучается процесс резания горной породы резцом, который описывается в рамках нестационарной нелокальной модели неупругих деформаций. Численный метод решения двумерной динамической модельной задачи основан на методе конечного элемента в смешанной постановке. Численное моделирование показало, что в рамках данной модели можно определить как характерный размер скола, так и оптимальную глубину резания, при условии, что известны неклассические модули породы, используемые для описания неупругой среды в рамках новой модели.

Ключевые слова: разрушение горной породы, резание горных пород, неупругость, неевклидовы деформации, метод конечного элемента.

NONLOCAL MODEL OF INELASTIC DEFORMATIONS APPLIED TO DYNAMIC PROBLEM OF ROCK FRACTURING

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The major factor of well drilling with PDC bit is a dynamic interaction of cutting tool and rock. In this paper non-stationary nonlocal model of inelastic deformations is applied to rock cutting with cutting tool problem. The suggested numerical solution of 2-dimensional dynamic problem is based on mixed finite element method. The nonlocal model leads to the appearance of two non-classical material constants that by analogy with classic model, can be called ’inelastic’ moduli. Numerical modeling has proven that is possible to predict both chip size and depth of cut within the scope of the suggested model if only the non-classical moduli are defined.

Key words: Rock fracturing, rock cutting, inelasticity, non-Euclidean deformations, mixed finite element method.

The major factor of well drilling with PDC bit process is a dynamic interaction of cutting tool and rock i.e. rock cutting. The difficulties of mathematical description of the rock cutting process, as it is emphasized in Cherepanov [1], arise from the elongated plastic zones around the cutting edge of a cutter and the interaction of multiple fractures generated from cutting. Cutting the rock formation with an apparent shear plane typically occurs under the brittle mode with cuttings formed as rock particles. The size of the rock particles is characteristic for the cutting process. The main experimental results of the cutting process are well studied (e.g. see Borisov [2]) and are typically reduced to describing the key patterns of the transitional process leading to the steady mode, as well as to characteristic features of the steady mode. On the other hand, the steady cutting mode is characterized with the measureable force of resistance to cutting, including cases when it is a function of the linear velocity of the cutter (Cherepanov [1]). Any theoretical model of the rock cutting process under the brittle fracturing mode proposed must confirm the experimental results. Adding new characteristic features of the cutting process does not bring more clarity to the physics of this phenomenon. The main problem of the rock cutting process may be reduced to finding the characteristic scale of formation fracturing under the conditions of a load applied to the cutter (weight on bit and torque on bit), taking into account the features of the stressed state of the formation in the vicinity of the cutter tip. The presented paper is providing an answer to the question using numerical modeling of rock cutting based on non-stationary nonlocal model of inelastic deformations [3].

In the Guzev paper [4], the following fact was noted: accounting for plasticity in the classical nonlinear theory of elasticity takes the deformed field of the stressed state outside of the Euclidean space (in the general case, the deformation metrics tends to become Riemann metrics). For the isotropic systems, such deformations are characterized by nonzero invariants of the Ricci tensor. Under the conditions of the plastic flow, it is the curvature of the deformation space that is the linear invariant. Then Gusev used the curvature as an incompatibility parameter for building stationary solution of the zonal disintegration problem. As a result, a structure of periodical fractured zones observed around mining pits was achieved.

Using the measure of deformation incompatibility as the basis, the definition of R is established as a second-order invariant of the deformation tensor ε: $-\frac{R}{2} = \Delta\varepsilon_{jj} - \partial_i\partial_k\varepsilon_{ik}$. Let's introduce destruction γ – a conjugated intensive pair of the extensive incompatibility parameter R in the terms of the non-equilibrium thermodynamics as $\gamma = \beta\varepsilon_{jj} + \alpha R$. Here α and β are parameters of state equation

$$e_0 = \text{const} + T_0(s - s_0) + \lambda\varepsilon_{jj}^2 / 2\rho + \mu\varepsilon_{ik}\varepsilon_{ik} / \rho + \beta R\varepsilon_{jj} / \rho + \alpha R^2 / 2\rho,$$

where ρ is the density and λ, μ denote elastic moduli. Parameters α and β are considered as new material parameters referred to as 'inelastic' moduli. Let's introduce the stress tensor σ_{ik} and velocity of the deformed medium v. Then motion equations for small strains with presence of destruction field are expressed as:

$$\rho\dot{v}-\partial_k\sigma_{ik}=0,\ \dot{\varepsilon}_{ik}-\left(\partial_k v_i+\partial_i v_k\right)/2=-\bar{\varphi}_{ik}-\varphi_{jj}\delta_{ik}/3,\ \sigma_{ik}=\lambda\varepsilon_{jj}\delta_{ik}+2\mu\varepsilon_{ik}+\beta R\delta_{ik},$$

$$\varphi_{jj}=\zeta\left(\sigma_{jj}-4\Delta\gamma\right),\ \bar{\varphi}_{ik}=\xi\left[\left(\sigma_{ik}-\sigma_{jj}\delta_{ik}/3\right)+2\left(\partial_i\partial_k\gamma-\Delta\gamma\delta_{ik}/3\right)\right]. \tag{1}$$

Here ζ and ξ are plastic (Maxwell relaxation) moduli. Note that as R and γ are conjugated to each other only one of them can be used independently.

In this paper the rock medium' behavior in the vicinity of a rigid moving cutter is analyzed numerically in scope of the nonlocal model of inelastic deformations. The mixed finite element solver presented by E.V. Vtorushin in [5] is applied. The computational domain is a step of 1 cm in height on a rectangle of 5 cm in height and 24 cm in length (Fig. 1). The external boundaries are far enough from the rock/cutter interaction zone to exclude their significant effect. The step's base is fixed rigidly. The surface of the step's riser moved with the constant velocity $u_0=150\,\text{cm/sec}$. Such linear velocity is typical for the cutter at a distance from a center of a bit while drilling at 120 rpm.

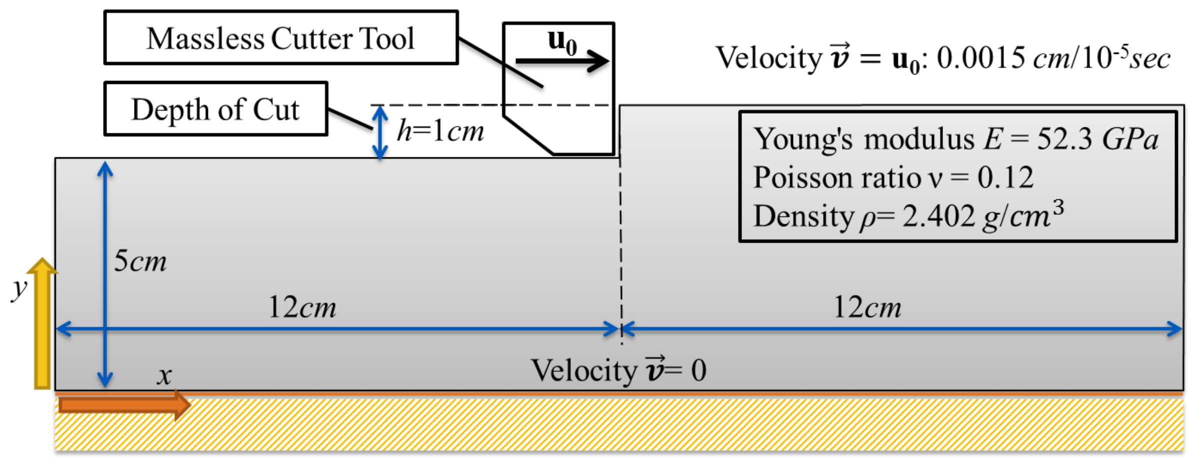

Fig. 1. Stair step sample of rock with moving riser face

Figure 2 presents the value of the destruction γ for α=0.04446, β=-0.5, ζ=0.125, ξ= 0.0625. By the time moment $t=37.5\cdot10^{-5}$sec the field of γ takes the characteristic periodic structure with a manifested failure scale. The destruction parameter reaches its maximum value at the first (closest to the cutter's tip) peak.

Figure 2a shows the destruction peak is formed near the cutter's tip as well as attenuating destruction waves. Fig. 2c shows possible cleavages formed in the direction of cutting, and Fig. 2d shows the loose layer forming in the depths. Figures 3 and 4 show the sensitivity domain of the solutions of interest relative to the "inelastic" modulus α. Set β= -1/3, ζ= 0.125 and ξ = 0.0625. The calculations were performed for four values of the modulus α: (0.15067, 0.06841, 0.04 and 0.03). Corresponding "weakened" modulus [5] $\bar{\lambda}=\lambda-\beta^2/\alpha$ was : (0.9λ, 0.8λ, 0.62λ and 0.5λ).

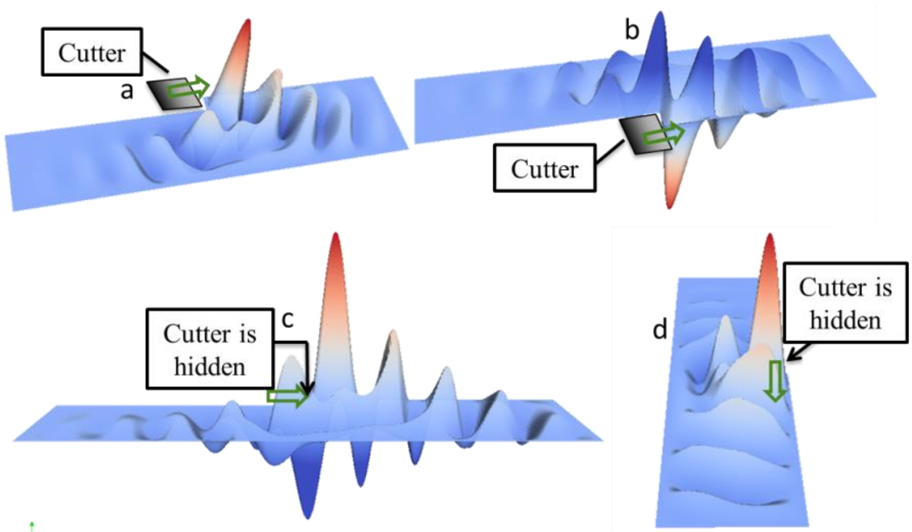

Fig. 2. Three-dimensional surface $\gamma(x, y)$ at time moment t= 37.5 10^{-5} sec

Figure 3 demonstrates color charts of the volume plastic deformations φ_{jj} at moment t = 75 · 10^{-5} *sec*. Modulus α has a direct effect on the characteristic scale of the failure zone. There is spatial periodicity in the zone. Its period increases as α decreases ($\bar{\lambda}$ ”weakening”). The few first failure zones demonstrate there is a characteristic scale for the following rock defragmentation (chip extrusion).

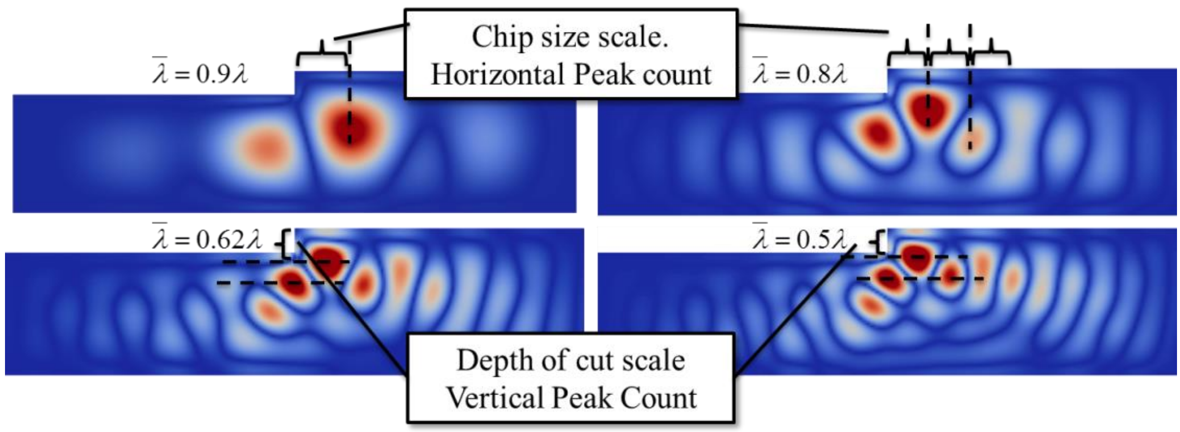

Fig. 3. Dependence of the volume plastic deformations on modulus α

Figure 4 shows color charts of the shear plastic deformations $(\bar{\varphi}_{ik}\bar{\varphi}_{ik})^{1/2}$ at moment t = 75 · 10^{-5} *sec*. Note that the rock fracturing process can be considered as an accumulation of shear plastic deformations that reach their critical level followed by rock fragmentation (i.e., instant strain energy release and appearance of new surfaces). The possible fragmentation lines are marked in dash lines.

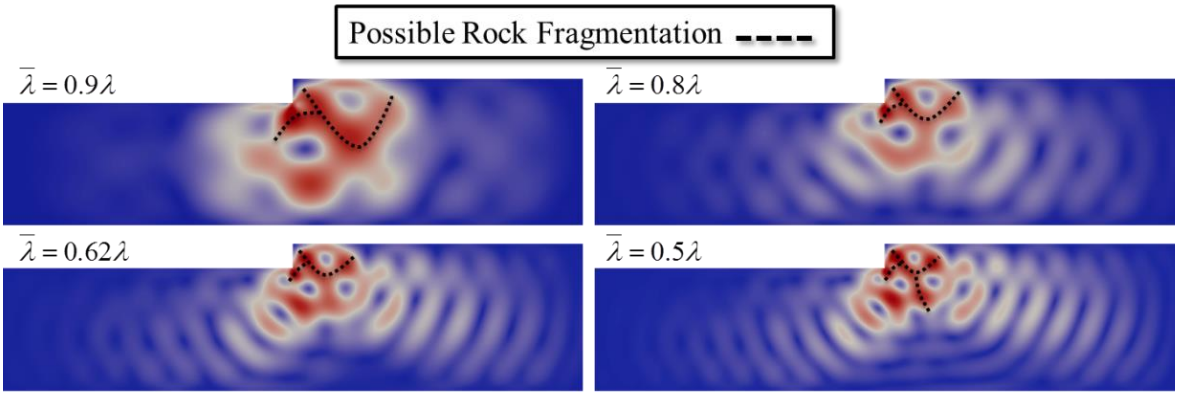

Fig. 4. Dependence of the shear plastic deformations on modulus α

The four subfigures of Figures 3 and 4 demonstrate chip size dependence on modulus α.

CONCLUSION

In this paper, the nonlocal dynamic model of inelastic deformations was applied for solving dynamic problem of failure zone formation while rock cutting, and an example of non-stationary process lead to the establishment of disintegration field causes the rock failure was provided. To make it possible, the thermodynamically consistent dynamic theory of zonal disintegration was exploited. The numerical investigation of the model 2-dimensional rock cutting problem confirmed that: a zone of plastic deformation of a rock has a characteristic scale of rock failure and the nonclassic α modulus is responsible for the failure scale caused by destruction.

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