Concerning the capability of monitoring the condition of coal bed by tomography based upon the representation of object model using Chebyshev polynomials

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Abstract. 3D geomechanical model of "Vorkutinskaia" mine, which allowed describing the development of stressed and deformed state of coal bed rock mass, has been developed and realized in numbers. Using empirical dependences of longitudinal waves velocity V on mean stress σ established by laboratory testing data, 3D distribution of V has been plotted. First arrival time tomography task, based upon the approximation of a bed geometrical model by Chebyshev polynomials, in order to give appraisal to the applicability for bed velocity structure reconstruction, has been analysed. With the use of data on dynamic events, registered by permanent stations, the object tomography has been prepared and 3D field of elastic waves velocities in highlighted part of area under study. It enables essential opportunity of stress state, if functions $V(\sigma)$ for rocks building up the massif are known. **Key words:** coal-rock massif, 3D model, tomography, Chebyshev polynomials, stress field reconstruction

1 Introduction

The safety of mining is based upon two major elements: optimal technology of deposit development called upon ensuring not only ceiling volume of production, but as well the level of stresses not exceeding the critical one [1]; rock mass state operation monitoring system [2-4] is designed for the collection of seismoacoustic and deformographic and other direct or indirect information of geomechanical fields, according to which analysis findings, preventive measures on the mitigation of emergency occurrence risks may be taken as well as changes in mineral wealth mining may be introduced. Generally accepted criterion of such information appraisal does not exist since all monitoring systems function in the conditions of uncertainty and, as a rule, use statistical methods of the detection of spatio-temporal regularities of distribution of stochastic fields parameters which directly or indirectly characterize the degree of fracturing in the elements of the object under control [5-10]. In [11], it is noted that long-and mid-range forecast and seismic risk appraisal

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(SRA) are used in mining operations planning. However, general opinion is that short-range SRA currently is not sufficiently reliable, despite significant efforts. Although, it was proven that a this is a hard task, it is necessary to take efforts on SRA technology improvement and further.

There are several directions of this subject development trends. For example, forecast of mine bumps may be improved by means of the integration of seismic, deformation and mining-engineering data with geomechanical modelling of rock mass trend. Precisely such approach was realized in [12,13] when the appraisal of rock mass condition was performed using stochastic and deterministic data within the frames of geomechanical model: regressional dependences between the parameters of seismic emission and integral characteristics of stress field have been prepared for various sections of the object under control. This allows verifying the model in terms of forensic analysis [14] forecasting the number and total energy of man-triggered events on the distribution of stresses, calculated in accordance with the long-range mining plan. In [15,16], new approach to modeling of current stressed and deformed state of a deposit mined was theoretically justified by the data of passive and/or active tomography and experiments on the determination of empirical dependence of longitudinal waves velocity on average stress.

With the use of data from [17], detailed 3D model of the mined section of "Vorkutinskaia" mine has been prepared in the first part of the work. In the second part, the capability of the application of tomography based upon the approximation of coal bed geometry by Chebyshev polynomials [18] has been justified.

2 Geomechanical model of "Vorkutinskaia" mine section

2.1 Object geological structure

"Vorkutinskoe" deposit represents brachy-synclinal fold with the dimensions of 30×12 km. Geological structure of the deposit is represented by alternating sandstones, aleurolites and coals with thicknesses from 3 to 100 m. Tectonically, the mine field is simple therefore discontinuities were not considered in geomechanical model. "Troinoi" bed (average thickness 2.85 m) is the upper commercial bed.

2.2 Geomechanical model description

In order to prepare the 3D model of the object under study, mining plan was digitized. The dimensions of computational area D are 840×1570×330 m, the upper border is located at the depth of 590 m from daylight surface, the thickness of coal bed is 3 m. Finite element discretization of the area (about 500 thousands) was performed in accordance with the structural features of coal bed and mined-out space configuration. Discretization pitch by horizontally is 10 m, vertically (z-axis) — 0.5 m in the bed, and gradually increases by moving away of it.

The properties of rocks (density ρ, Lamé parameters λ and μ), building the massif are given in Table 1.

Table 1. The properties of rocks.

Rock	ρ, kg/m^3	λ, GPa	μ, GPa	A, m/s	B, m/s	C
Enclosing rocks	2,200	20	20	4,212	1,498	0.592
Coal	1,500	15	10	2,698	484	0.779

Information on horizontal stresses in natural field borrowed from [19]: in the neighbour of "Vorkutinskaia" mine, there is a faulting geodinamic mode, lateral repulse factor in the direction of mining operations development is q_y=0.6, in orthogonal direction — q_x=0.4. The deformation of medium is described by the system including: equilibrium equations (1), Hook's law (2) and Cauchy equations (3)

$$\sigma_{ij,j}+\rho g\delta_{iz}=0 \tag{1}$$

$$\sigma_{ij}=\lambda(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})\delta_{ij}+2\mu\varepsilon_{ij} \tag{2}$$

$$\varepsilon_{ij}=0.5(u_{i,j}+u_{j,i}) \tag{3}$$

where σ_{ij} and ε_{ij} – components of stresses tensors and deformations ($i, j = x,y,z$); u_i — of shifting; δ_{ij} — Kronecker delta. System (1)(3) with relevant boundary conditions on ∂D is realized through finite-element technique using original code [20].

2.3 Calculation results

On fig. 1a, by way of example, the distribution of horizontal stresses σ_{yy} in section x=420 m (negative values correspond to compression) is shown. Expectedly, in the neighbour of a mine face, there is stress concentration.

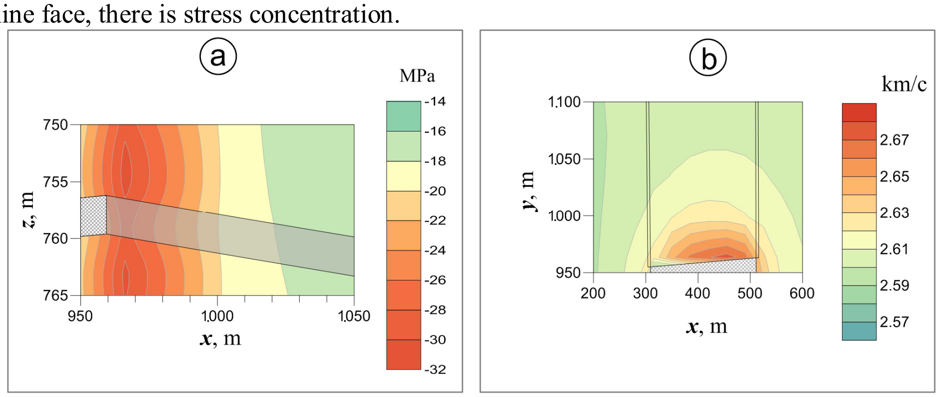

Fig. 1. Isolines of horizontal component of stress tensor σ_{yy} (MPa) in vertical section x=420 m (a); the distribution of longitudinal waves V in a bed mid-section (b).

Laboratory experiments [21] for the determination of seismic waves distribution velocity in loaded rock samples allowed establishing the dependence of longitudinal waves velocity V on average stress σ

$$V(\sigma)=A-B\cdot\exp\,(C\sigma/\sigma_0), \tag{4}$$

where empirical constants A, B and C are given in Table 1, σ_0=5 MPa. On fig. 1b, the lines of level of velocity V in a bed mid-section (crosshatched zones – mined-out space), calculated by (4) where $\sigma=(\sigma_{xx}+\sigma_{yy}+\sigma_{zz})/3$, are represented. Obtained distributions $V\,(x,y,z)$ were being used further on as a precise model in tomography.

3 Tomography based upon the representation of coal bed model by Chebyshev polynomials

3D model of the medium containing coal-rock massif is represented in the shape of a set of layers L_j (j layer index) divided by surfaces Z_j. In each L_j, the function of slowness (value reciprocal velocity) $S_j(x,y)$, which depends only on lateral coordinates x and y defined. Function S_j is determined through Chebyshev polynomials of zero-third order

$$S_j(x,y)=C_0+C_1x+C_2y+C_3xy+(2x^2-1)C_4+(2y^2-1)C_5+ \\ y(2x^2-1)C_6+x(2y^2-1)C_7+(4x^3-3x)C_8+(4y^3-3y)C_9, \tag{5}$$

where coefficients C_C are various for each bed. Surfaces Z_j are described by Chebyshev polynomials similarly to (5) with own expansion factors. The use of Chebyshev polynomials for the parametrisation of the model allows obtaining significant calculative advantages: travel-time information and their derivatives by parameters determining ray are calculated analytically.

3.1 Point-to-point ray tracing by bend method

We suppose that in each layer, the ray represents the length of a straight line, described depicted by coordinates of points of interception with the upper (x_j,y_j,z_j) and lower $(x_{j+1},y_{j+1},z_{j+1})$ surfaces,. Note that z_j depends on (x_j,y_j) through the representation of Chebyshev surfaces. Thus, in order to trace a ray satisfying Fermat's principle, it is necessary to minimize objective functional

$$T=\sum T_j(x_j,y_j,x_{j+1},y_{j+1}) \quad (6)$$

by variables (x_k,y_k) with fixed position of a source and receiver. The search of minimum T is performed by non-linear conjugate gradient method. For that end, analytical forms for the information of travel-time T_j and derivatives of T_j along current trajectory are depicted.

3.2 Numerical studies

In order to study the applicability of 3D tomography algorithm created based upon Chebyshev polynomials, tresses (p. 2), and with the use of (4) precise distribution $V(x,y,z)$ were calculated. Then, the part of the bed, planned for mining, and, accordingly, for monitoring, was selected and transferred to terms of Chebyshev polynomials.

It should be noted that the average velocity in the bed is about 2,600 m/s, in enclosing rocks — 3,800 m/s, the bed has a rugged relief. Therefore, the three-dimensional task, standard methods of rays tracing and tomography based upon them are inapplicable. Exactly, for these reasons, waves tracing method with the approximation of Chebyshev polynomials functions is used here [18].

At "Vorkutinskaia" mine, accepted the following observation system for registration of seismic events (fig. 2): 5 receivers with spacing of 10 meters are located along board gates. Let 50 sources are identified in a bed.

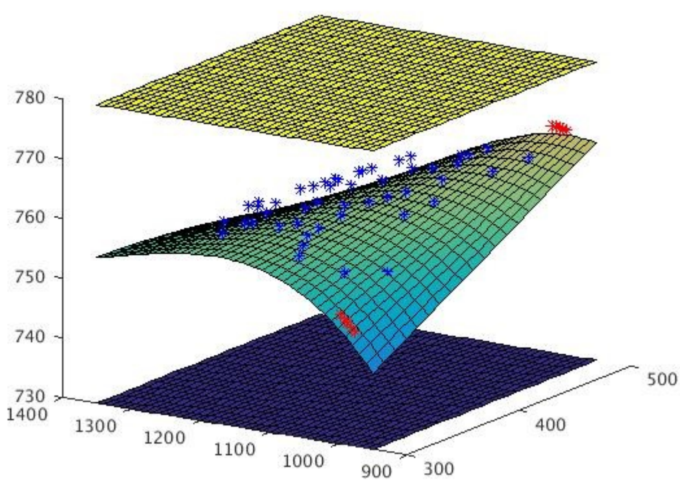

Fig. 2. Coal bed relief and observation system.

Tomography results for such observation system are represented in fig. 3. Initial velocity model for coal bed was selected as homogeneous (*V*=2,600 m/s). It is apparent that tomography gives good result, almost identical to precise model in highlighted area.

4 Conclusions

Tomography, based upon the representation of geomechanical object model using Chebyshev polynomials in respect to the task of monitoring coal bed by seismic data, has been studied. Such representation allows:

– briefly describing bed relief and distribution of velocities in it;
– correctly solving the task of tracing in contrast thin bed;
– substantively reducing the number of required parameters compared to standard grid model representations what determines solution reliability even in conditions of lack and/or noisiness of seismic information.

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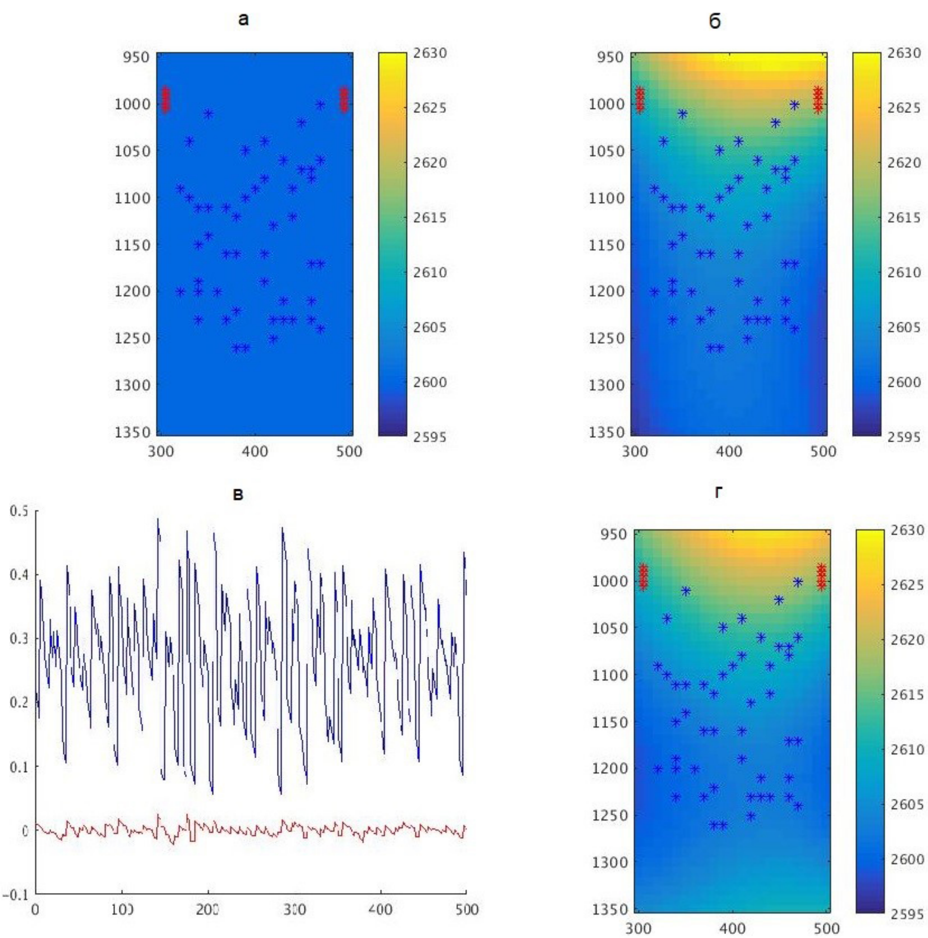

Fig. 3. Initial (a) and precise (b) velocity models; tomography result – the distribution of velocity in a coal bed (c); time mis-tie: blue in the initial model, red — after tomography (d).

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