Numerical study of the influence of rock massif heterogeneity on its geomechanical state in the vicinity of mine workings for substantiating the underground coal mining digitalization

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Abstract. Based on the results of a numerical experiment, the patterns of stress-strain state distribution of inhomogeneous rock massif in the vicinity of a worked-out area and development working, protected by a coal pillar, were revealed.

1. Introduction

In modern coal mines, to ensure high-performance work of complex fully-mechanized longwalls, a multi-track scheme is used for the preparation and mining of extraction pillars. In this case, the geomechanical task arises that it to ensure the operational stability of the development workings protected by coal pillars with a minimum width of these pillars. The minimum width of pillars and maximum deformations of rocks in the vicinity of the development workings depend on many factors specified in the current guidelines [1-4]. However, in the documentation for the conduct of mining operations, mining, geological and technical conditions, as a rule, are assumed to be deterministic, and the influence of the variability of the properties of the rock massif on the technological and geomechanical characteristics and parameters of geotechnology within the entire excavation area is not always taken into account [5].

In connection with the transition of the traditional design and planning system of mining operations to automated technologies [6] using digital models of mineral deposits and probabilistic methods of mathematical modeling when optimizing options for the development of mining operations, an urgent scientific and practical task of identifying patterns and dependencies of the main geomechanical and technological parameters of production and development faces from the structural and physical heterogeneity of the rock massif.

To solve the problem posed in this work, mathematical modeling is applied with the numerical implementation of the equations of elastic and elastoplastic deformation of rocks by the finite element method. A numerical experiment was carried out, in which the basic and alternative options of the space distribution of geomechanical parameters digital model were considered, and, based on the results of comparing the obtained values, the optimal ratios of single or group of variable factors of heterogeneity and indicators of production and preparation faces were established. To assess the adequacy of the obtained numerical experiment results, full-scale measurements of deformations of the rock massif in the vicinity of underground mine workings and on the undermined territories of the earth surface were used.
As the subject of the study, the regularities of the distribution of the parameters of the stress-strain state of a heterogeneous rock massif in the zone of joint influence of coal pillars, stope and development workings are considered. The object of the research is a heterogeneous rock massif with variable properties in space, including a system of mutually influencing coal pillars, stope and development workings.

2. Research methods

The heterogeneity of rock massifs should be understood as the spatial variability of the petrographic, physical and mechanical properties of rocks [5, 7]. Some authors identify the concepts of variability and heterogeneity with a variety of properties of a rock massif, variable in time and space [8]. The physical heterogeneity of the massif depends on its mineralogical and petrographic components. Within the framework of the task in this article, the most interesting is the heterogeneity of the deformed, stressed and structural state of the rock massif. It is accepted, according to the degree of fragmentation of the rock massif, to distinguish the structural heterogeneity of three orders [9-11]: tectonic faults and discontinuities, linear dimensions of structural objects more than 10 m, macro-fracturing with dimensions of structural blocks 0.1-10 m, micro-fracturing with a distance between fractures less 0.1 m.

Microinhomogeneity characterizes the variability of a rock of one lithological type, its structural, physical-mechanical and filtration parameters. Macroheterogeneity is manifested in the change of rocks of different lithological types, for example, rock layers and coal seams. According to the form of manifestation, macroinhomogeneity can be zonal, layered, block, etc.

The structural dissection of the rock massif leads to stepwise differences in deformation characteristics and the formation of stress concentrators in the nodal contact zones of the blocks, that is, the concepts of mathematical and actual solidity of the rock massif do not coincide. Under these conditions, it is necessary to change the traditional approaches to constructing the finite element mesh so that the shape and size of the finite elements correspond to the structural elements of the rock massif. Accordingly, in mathematical models of rock mechanics, one should consider not solid, but anisotropic rock massifs. Since in the anisotropic rock massif on the diagrams the deformation moduli in the tension and compression zones differ by 1-2 orders of magnitude [10, 12-14], it becomes urgent to use the theoretical foundations of multi-modulus materials for predicting the stress-strain state of a geomassif [15].

In general, a diagram of a model of rock massif, coal pillar between the development working and a gob is shown in figure 1. A vertical section along the dip of an inclined seam is considered, the length of the section is up to 2 km. The height of the section is taken according to the depth of development, which is measured as the vertical distance from the roof of the ventilation drift to the earth surface. A coal seam with a thickness of 2.5 m was mined in an excavation column and presented in the form of a gob area with caved roof rocks. The length of the mined-out area (face length) varied according to the practical experience of the Kuzbass mines in the range of 200-300 m.

**Figure 1.** Design diagram of the rock massif in the vicinity of the gob area, ventilation drift and coal pillar between them.
The ventilation drift of the extraction pillar located below the dip of the seam is protected by a pillar coal, the width of which varied in different versions within the range of 20-60 m. The ventilation and conveyor drifts of the spent upper column are not supported.

Structural heterogeneity was taken into account by changing the angle of incidence of the seam $\alpha = \pm 15^\circ$, variable thickness and strength of rock layers, inclusion of fictitious weakened layers in the form of satellite layers of non-working thickness at the contacts of adjacent rock layers, inclusion of rock layers in the coal seam. Physical heterogeneity was taken into account by changes in the strength of coal or rocks within a separate layer, fracturing and gas content of coal seams.

When forming the research program and options for structural heterogeneity, the well-known hypotheses of deformation of underworked roof rocks, including the theory of beams by G.N. Kuznetsov, plates A.A. Borisov, the limiting balance of rocks by G.L. Fisenko, block caving S.T. Kuznetsov and P.M. Tsimarevich; roof deformation schemes K.V. Ruppenite, H. Kratzsch, H. Labasse and other founders of theories and hypotheses of rock displacement. As a basis for identifying the criteria for structural heterogeneity, a classification was adopted that takes into account the stratification of underworked rock layers with the opening of contacts into packets of slabs and beams in the form of a false, immediate and main roof [16, 17].

Taking into account a variety of variable options for changing the heterogeneity (table 1), a large amount of information was obtained, for the analysis of which 11 characteristic points (zones), indicated in all figures of this paper, were identified on all models.

**Table 1. Basic options of rock massif models.**

| Model Option Number | rock massif | Heterogeneity | Heterogeneity | Heterogeneity | coal seam |
|---------------------|-------------|---------------|---------------|---------------|-----------|
|                     |             | direct roof and soil | main roof | overlying strata | coal seam |
| 1                   | Layered massif of heterogeneous strength with separation of plates packets of homogeneous strength layers in a packet | Packet of plates of uniform strength $\sigma_{\text{com}} = 35$ MPa | Packet of plates of uniform strength $\sigma_{\text{com}} = 60$ MPa | Packet of plates of uniform strength $\sigma_{\text{com}} = 40$ MPa | Coal seam of uniform strength $\sigma_{\text{com}} = 10$ MPa |
| 2                   | Layered massif of non-uniform strength with separation of packets of plates of homogeneous strength of layers in a packet with weakened contacts between plates | Pack of layers of homogeneous strength $\sigma_{\text{com}} = 35$ MPa with weakened contacts between packets $\sigma_{\text{com}} = 10$ MPa | Pack of layers of uniform strength $\sigma_{\text{com}} = 60$ MPa with weakened contacts between the packets $\sigma_{\text{com}} = 10$ MPa | Pack of layers of uniform strength $\sigma_{\text{com}} = 40$ MPa with weakened contacts between the packs $\sigma_{\text{com}} = 10$ MPa | A layer of uniform strength $\sigma_{\text{com}} = 10$ MPa with weakened contacts with wallrocks $\sigma_{\text{com}} = 5$ MPa |
| 3                   | Layered massif, heterogeneous in strength with weakened contacts between layers | A packet of layers non-uniform in strength $\sigma_{\text{com}} = 30$-40 MPa with weakened contacts between layers $\sigma_{\text{com}} = 10$ MPa | A package of layers, non-uniform in strength, $\sigma_{\text{com}} = 40$-60 MPa with weakened contacts between layers $\sigma_{\text{com}} = 10$ MPa | A packet of layers, non-uniform in strength, $\sigma_{\text{com}} = 40$-50 MPa with weakened contacts between layers $\sigma_{\text{com}} = 10$ MPa | Non-uniform in strength $\sigma_{\text{com}} = 10$ MPa with weakened contacts between wall layers and the seam $\sigma_{\text{com}} = 5$ MPa |
Layered massif, non-uniform in strength with weakened contacts between layers with adjustment according to the results of field measurements

A packet of layers, non-uniform in strength \( \sigma_{\text{com}} = 30-40 \) MPa with weakened contacts between layers \( \sigma_{\text{com}} = 10 \) MPa

A packet of layers, non-uniform in strength \( \sigma_{\text{com}} = 40-60 \) MPa with weakened contacts between layers \( \sigma_{\text{com}} = 10 \) MPa

A packet of layers, non-uniform in strength \( \sigma_{\text{com}} = 40-50 \) MPa with weakened contacts between layers \( \sigma_{\text{com}} = 10 \) MPa

Non-uniform in strength \( \sigma_{\text{com}} = 10 \) MPa with weakened contacts between side layers and the seam \( \sigma_{\text{com}} = 5 \) MPa

Figure 2 shows a fragment of the design model for the horizontal seam with the location of a mesh of finite elements, a gob area and a ventilation drift protected by the coal pillar. The characteristic points and their numbers are located in the coal pillar (6, 7, 8) and at a distance of 0.5 m from the contour of the ventilation drift (8-11). The calculation of geomechanical parameters was carried out according to the author’s complex of problem-oriented programs [18].

Geomechanical parameters at characteristic points 1-11, used to identify patterns and dependencies of the main geomechanical and technological parameters of production and development faces on the structural and physical heterogeneity of the rock massif, are systematized for all zones in table 2.

**Table 2. Geomechanical parameters at characteristic points for different options of the rock massif model.**

| Point numbers on the model | Point coordinates, \( x; y, \) m | Geomechanical parameters for options of a rock massif model |
|---------------------------|-----------------------------------|---------------------------------------------------------|
| 1 option of the model: layered massif of heterogeneous strength with separation of packets of homogeneous plates | 2 option of the model: non-uniform in strength layered massif with separation of packets of plates of homogeneous strength of layers in a packet with | 3 option of the model: non-uniform in strength layered massif with weakened contacts between layers | 4 option of the model: layered massif of non-uniform strength with weakened contacts between layers with adjustment according to the |
by the strength of the layers in the packet
weakened contacts between plates
results of field measurements

Vertical displacements, elastic model / nonlinear, mm

| x | y | Vertical displacement, mm |
|---|---|--------------------------|
| x=80; y=500 | -134/-213 | -136/-215 | -144/-221 | -825 |
| x=110; y=170 | -262/-374 | -258/-371 | -280/-393 | -1443 |
| x=115; y=70 | -438/-562 | -445/-590 | -457/-610 | -2256 |
| x=120; y=40 | -489/-611 | -497/-654 | -513/-669 | -2418 |
| x=120; y=32 | -490/-650 | -498/-660 | -514/-670 | -2480 |
| x=42; y=10 | -87/-226 | -112/-207 | -115/-155 | -519 |
| x=21; y=5 | -78/-96 | -81/-109 | -84/-108 | -365 |
| x=3; y=-1 | -72/-83 | -58/-81 | -65/-75 | -256 |
| x=0; y=0,5 | -77/-110 | -82/-113 | -87/-123 | -308 |
| x=-3; y=-2 | -71/-77 | -59/-74 | -62/-78 | -243 |
| x=0; y=-4 | -37/-44 | -39/-43 | -36/-42 | -203 |

Vertical stresses, elastic model / nonlinear, MPa

| x | y | Vertical stress, MPa |
|---|---|---------------------|
| x=80; y=500 | +0.14/+0.09 | +0.09/+0.14 | +0.20/+0.13 | +3.06 |
| x=110; y=170 | -3.11/-3.04 | -3.16/-1.10 | -3.02/-2.84 | +4.46 |
| x=115; y=70 | -0.85/-0.90 | -0.61/-0.65 | -0.26/-0.54 | +10.06 |
| x=120; y=40 | +0.09/+0.10 | -0.06/+0.06 | +0.09/+0.03 | +18.14 |
| x=120; y=32 | +0.08/-0.05 | +0.10/+0.06 | -0.04/-0.02 | +8.26 |
| x=42; y=10 | -48.09/-46.99 | -66.80/-61.62 | -60.14/-46.01 | -87.04 |
| x=21; y=5 | -17.91/-17.14 | -18.36/-17.52 | -18.64/-17.52 | -33.64 |
| x=3; y=-1 | -17.70/-18.50 | -19.35/-18.88 | -19.82/-17.86 | -37.74 |
| x=0; y=0,5 | -2.48/-2.43 | -1.16/-1.15 | -1.10/-0.59 | -1.56 |
| x=-3; y=-2 | -17.95/-16.93 | -17.59/-16.65 | -18.14/-17.19 | -30.02 |
| x=0; y=-4 | -0.40/-0.38 | -1.32/-1.27 | -0.37/-0.10 | -2.20 |

The ratio of residual strength to the original, the model is nonlinear by IPR = 28

| x | y | Ratio of strength | IPR |
|---|---|------------------|-----|
| x=80; y=500 | 1.00 | 1.00 | 1.00 | 1.00 |
| x=110; y=170 | 0.92 | 0.64 | 0.49 | 0.11 |
| x=115; y=70 | 0.50 | 0.32 | 0.37 | 0.08 |
| x=120; y=40 | 0.40 | 0.30 | 0.29 | 0.27 |
| x=120; y=32 | 0.39 | 0.37 | 0.27 | 0.28 |
| x=42; y=10 | 0.10 | 0.12 | 0.18 | 0.03 |
| x=21; y=5 | 0.93 | 0.93 | 0.92 | 0.25 |
| x=3; y=-1 | 0.73 | 0.65 | 0.61 | 0.30 |
| x=0; y=0,5 | 0.66 | 0.58 | 0.38 | 0.62 |
| x=-3; y=-2 | 0.66 | 0.78 | 0.71 | 0.29 |
| x=0; y=-4 | 0.52 | 0.43 | 0.49 | 0.35 |

3. Results and discussion

As it follows from the results of numerical modeling for options 1-3, the geomechanical parameters, despite changes in the structural heterogeneity, changed insignificantly. It can be argued that there are tendencies for an 8-10% increase in vertical displacements in the shear zone and in the coal pillar, when taking into account the rock massif, weakened rock layers by contacts with strength, are 3-5 times less than the strength of adjacent layers.

In the vicinity of the entirely protected coal ventilation drift, the nature of the distribution of vertical displacements and stresses practically did not change. In the roof of the mine, the vertical compression stresses decrease by 2-3 times as the number of weakened rock layers along the contacts.
increases. The ratio of the residual strength to the original in the vicinity of the working also decreases in options 1-3.

The intensity of the decrease in the strength of rocks in the shear zone decreases as the distance from the seam roof to the earth surface increases.

Based on the results of numerical modeling, the regularities of the increase in the structural heterogeneity of the rock massif, arising under the influence of the reference rock pressure in the vicinity of mine workings, were revealed [19-21]. Figure 3 shows the graphs of the distribution of zones of destruction and pre-destruction of underworked rocks over the gob area.

Figure 3 shows that the rocks of the immediate and main roof are completely destroyed. At a distance of 100-120 m from the mined seam, rocks are destroyed in weakened contacts, and rock plates remain stable. The height of this zone corresponds to the boundary of the fracture zone, equal to 40 m, where \( m = 2.5 \) m – the recoverable thickness of the seam, which does not contradict the research results given in the monograph [22].

Figure 3. Distribution graphs of the ratio of the coal and rocks residual strength to the original strength after mining the coal seam, option 3 in tables 1 and 2 with weakened contacts.

Comparison of the results of modeling and field measurements of rock massif displacements [22-24] showed that analytical methods for calculating displacements of underworked rocks do not ensure that the predicted values correspond to the actual ones. In mining practice, according to the current “Rules ...” [23], the maximum subsidence of the underworked earth surface \( \eta_m \) is determined by the formula:

\[
\eta_m = q_o m N_1 N_2 \cos \alpha,
\]

where \( q_o \) is the relative maximum subsidence of the earth surface, with primary working in the conditions of Kuzbass \( q_o = 0.70 \); \( m \) – recoverable thickness of the seam, \( m = 2.50 \) m; \( N_1, N_2 \) - coefficients depending on the ratio of the size of the working to the average depth of development, with a face length of 200 m and a depth of development \( H = 468 \) m in figure 1 according to [23] \( N_1 = 1.00; N_2 = 0.49; \alpha \) - dip angle, \( \alpha = 15^\circ \).

With the specified values of the model parameters of the rock massif and workings according to (1) \( \eta_m = 0.83 \) m. The maximum subsidence of the earth surface, calculated by the finite element method (see point 1 in table 2) \( \eta_{m\text{fe}} = 0.22 \) m, which is almost 3.8 times less subsidence recommended in [23]. Accordingly, the calculated displacement values cannot be recommended for practical use. One of the
reasons for the significant deviations in the calculated and actual values of displacements of underworked rocks is the duration of the displacement process, which in Kuzbass conditions reaches three years, which is taken into account in the empirical formula (1).

One of the options for bringing the calculated parameters of the stress-strain state of the rock massif to those measured at coal mines is to adjust the displacements in the model according to the measured or recommended “Rules...” [23] values of horizontal and vertical displacements in the displacement trough on the earth surface. Another boundary surface is the underworked rock at the top of the formation, where subsidence is equal to its removable thickness.

After substitution of the maximum displacements of the earth surface and the roof of the mined-out seam, the 4th option of the model was created and the geomechanical parameters presented in table 2 were obtained. According to table 2, the regularity of changes in the vertical displacements of underworked rocks during the transition from a linear model to a nonlinear model, taking into account the time factor, remains, but subsidence increases.

Figure 4 for comparison with the graphs in figure 3 shows the distribution of the ratio of residual strength to the original one (setting the input parameters of the model according to [23], option 4 in tables 1 and 2 with weakened contacts).

![Figure 4. Distribution graphs of the of the ratio of the coal and rocks residual strength to the original strength after mining the coal seam, option 4 in tables 1 and 2 with weakened contacts.](image)

According to the graphs in figure 4, within the zones of caving and fracturing, the heterogeneity of the rock massif is manifested through the formation of a block structure. According to table 2, the vertical stresses in the blocks significantly exceed the ultimate strength of the rocks, and tensile stresses are possible at the contacts of the blocks.

4. Conclusions
For assessment of the heterogeneity of the rock massif physical and structural heterogeneity are distinguished, the latter is classified in three orders: tectonic faults and discontinuities, linear dimensions of structural objects more than 10 m, macro-fracturing with dimensions of structural blocks 0.1-10 m, micro-fracturing with a distance between fractures less than 0.1 m.

In a numerical experiment, as the transition to nonlinear models with greater heterogeneity changes, the nature of pre-fracture of underworked rocks changes from smooth subsidence to the formation of a block structure, which is recommended to be used when calculating the parameters of the gas reservoir and the method of gas drainage from the gob.
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