Geomechanical justification of geotechnical situation in coal extraction with highwall mining system

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Abstract. One of the most effective approaches to reduction of coal loss in open pit within ultimate limits is extraction of coal reserves from the pit walls and bottom using the highwall mining systems. The high efficiency of the method is conditioned by minimal capital cost and reuse of the existing geotechnical infrastructure. On the other hand, the safe application of this approach depends on the rock mass quality. In mining practice, the major application area of the highwall mining systems is pitwall rock mass of damping jointing. In this connection, this paper aims to estimate influence of rock mass quality on stability of pit wall and underground openings (rooms and pillars). The set problem is solved by the finite element modeling of geomechanical situation for standard conditions of an open pit coal mine. The novelty of the research consists in more comprehensive inclusion of rock mass lithology, jointing, deformation and strength characteristics, initial stress state and structural features of technology in the problem solution.

1. Introduction
In coal mining, the open pit method is safer and more efficient than the underground method [1–6]. Unfortunately, this is only valid for shallow deposits.
A key constrain in the open pit coal mining is the increase in cost of coal production in deeper levels due to enlarged volume of stripping. As a rule, as soon as the ultimate stripping ratio is reached, the open pit method becomes inefficient and mining is terminated in open pit mines. I the meanwhile, pit walls contain considerable coal reserves. Therefore, it is required to find or develop engineering solutions aimed to improve completeness of coal extraction.
A singular method efficiently applicable within ultimate pit limits with available infrastructure is highwall mining [7–9]. The area of sustainable use for the highwall mining method is mainly rock masses with damping jointing [10–15]. In this case, in the absence of the reliable knowledge on rock mass belonging to such category of damage, it required to provide the sound and qualitative justification of safe operation of the highwall mining system.
Thus, this research is aimed to assess the influence of the rock mass quality on the stability of pit wall rock mass (rooms+pillars).

2. Mining method and research technique
In itself, the highwall mining method is an analog of the room-and-pillar system (Figure 1). Unlike the classic approach, this system includes preparation of the front by means of accessing coal seam in the
pit wall to afford contact with the winning machine attachment while the main drive control, power units, hydraulic and other mechanisms of the machine remain on the surface [16–19].

**Figure 1.** Highwall mining technology: 1—highwall mining system; 2—pitwall; 3—coal bed; 4—rib pillar; 5—room; 6—panel pillar.

As against the other technologies, namely, mechanical–hydraulic, water jet, drilling, augering, the highwall mining systems are advantageous for: high safety and productivity, low operating cost, minimal commissioning period and payback time.

The stress–strain analysis of rock mass was carried out by the FEM-based modeling of typical conditions in an operating open pit coal mine with coal extraction in single layer (mining height of 3 m) (Figure 2). The analysis involved the geotechnical situation in the pit wall rock mass 130 m away from the ultimate pit limit.

**Figure 2.** Typical geotechnical situation in coal extraction by highwall mining system.

The modeling took into account the rock mass quality. The latter was estimated as the reduced elasticity and strength of rocks in the zone of jointing (the modeling used the effective modulus of elasticity), i.e., the real jointed rock mass was replaced by a continuum medium of equivalent deformability.

The stability of the geotechnology elements was assessed [19–23]: by the theory of major normal tensile stresses—$$\left| \sigma_3 \right| \leq K_{SW} \sigma_t$$ (where $$\sigma_3$$—minimal tensile principal stresses obtained from elastic solution, MPa; $$K_{SW}$$—structural weakening factor; $$\sigma_t$$—ultimate tensions strength of rocks, MPa); by the Mohr–Coulomb theory—$$2C \cos \phi + (\sigma_1 + \sigma_3) \sin \phi \geq (\sigma_1 - \sigma_3)$$ (where $$C$$—cohesion, MPa; $$\varphi$$—
internal friction angle, deg; $\sigma_1$ and $\sigma_3$—maximal and minimal principal stresses, respectively); and from the comparison of intensity of the principal stresses with ultimate compression strength of rocks—$\sigma_1 - \sigma_3 \leq \sigma_c$ (where $\sigma_c$—average strength).

The integrated analysis of the input geological data and the current geotechnical situation, as well as structure and safety of geotechnology produced 2 modeling scenarios of highwall mining:

**Scenario 1**—joint extraction of rib pillars and inter-block pillars;

**Scenario 2**—extraction of room fendesr with intact panel pillars.

3. Results and analysis

The modeling results are presented as contour lines of stresses and delineated zones of possible rock failure (colored in black).

Figures 3 and 4 show patterns of the maximal shear stress $\tau_{\text{max}}$ and areas of instability in elements of room-and-pillar geotechnology of coal extraction by highwall mining system deep in rock mass 130 m away from the ultimate pit limit depending on rock mass jointing for Scenario 1.

**Figure 3.** Distribution of maximal shear stresses $\tau_{\text{max}}$ in rock mass in Scenario 1.

**Figure 4.** Damaged rock zones in the geotechnology structure in Scenario 1: (a) by tensile stresses; (b) by the Mohr–Coulomb criterion at $K_{\text{SW}} = 0.05–0.1$; (c) by the Mohr–Coulomb criterion at $K_{\text{SW}} = 0.2–0.25$; (d) by $\sigma_1 - \sigma_3 \leq \sigma_c$ at $K_{\text{SW}} = 0.05–0.1$; (e) by $\sigma_1 - \sigma_3 \leq \sigma_c$ at $K_{\text{SW}} = 0.2–0.25$.

Figures 5 and 6 demonstrate the results of modeling for Scenario 2.
Figure 5. Detailed distribution of stresses in rock mass in Scenario 2: (a) maximal principal stresses $\sigma_1$; (b) minimal principal stresses $\sigma_3$. 
Figure 6. Damaged rock zones in the geotechnology structure in Scenario 1: (a) by tensile stresses; (b) by the Mohr–Coulomb criterion at $K_{SW} = 0.05–0.1$; (c) by the Mohr–Coulomb criterion at $K_{SW} = 0.2–0.25$; (d) by $\sigma_1 - \sigma_3 \leq \sigma_c$ at $K_{SW} = 0.05–0.1$; (e) by $\sigma_1 - \sigma_3 \leq \sigma_c$ at $K_{SW} = 0.2–0.25$.

Figure 7. Damaged roof rocks and rib pillars in full-scale conditions of mining.

Based on the accomplished calculations for the considered geotechnical scenarios of highwall mining, it has been found that:

The stress state parameters and delineated high-stress (stress concentration) and stress relaxation zones imply (in case of the worst situation of poor quality of highly jointed rock mass at $K_{SW} = 0.05–$
0.1) post-limiting state from the view point of deformation and strength characteristics. The most unfavorable conditions are observed in the roof and floor of the rooms, as well as in the rib pillars and panel pillars, safety of which is governed by the rock mass strength. Owing to considerable spans in the room, vast zones of tension appear in the roof and floor, and promote rock falls (Figure 7a). The maximum values of the principal compressive stresses $\sigma_1$ are observed in the pillars and in the margins of mining zone;

The modeled areas of instability (critical deformation) in rock mass agree well with the field data (Figure 7). Depending on the assumed criterion of rock mass stability and jointing (change in strength characteristics with regard to structural weakening), the predicted damaged rock zones are connected one way or another with rib pillars and panel pillars, as well as with roof and floor of the rooms, and zone of mining. According to the numerical modeling, the zones of possible failure in rock mass conform with the concentration zones of the compressive, tensile and shear stresses. The sizes of these zones change depending on the strength characteristics of rocks (i.e. the obtained values of stresses in the highly jointed rock mass estimate the discussed geotechnical structures and exposures as unstable).

Mining safety requires continuous monitoring of areas of high stress concentrations with assessment of influence exerted by these areas on working conditions.

4. Conclusions
The reduced strength of pillars and and roof rock falls in rooms is mainly conditioned by the high compressive, tensile and shear stress effective in rocks mass (higher than the limit characteristics of rocks). The major effect on rock mass stability is exerted by its structural weakening due to natural and anthropogenic factors.

On the whole, the mathematical modeling of stress state and stability of geotechnical structure elements during highwall mining is applicable for prediction of rock falls and doe development of safety measures in high-stress rock mass areas.

The control over migration of hazardous zones in the course of mining requires continuous geological and surveying monitoring of the occurrence conditions of coal seams.

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