Reduction of mine methane emissions for ensuring sustainable development of geotechnologies in the transition to Industry 3.0

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Abstract. The need to apply innovations in the field of environmental modernization is related to all branches of the domestic industry. Its particular relevance for the enterprises of the mining complex necessitates the neo-industrialization of the integrated development of the subsoil resources. The article defines the conceptual conditions for the development of sustainable geotechnologies. The nonlinear nature of the dynamics of methane release into the methane drainage boreholes has been proved and an explanation of the mechanism for its implementation under the influence of situational geomechanical conditions for developing reserves of high-gas-bearing coal seams has been proposed.

1. Introduction

Innovative development of domestic geotechnical systems is possible only if there is no tangible gap in the technological paradigms of the developed and developing countries. In this regard, the work [1] is one of the first domestic fundamental research (in identifying ways to overcome these gaps), which laid the foundation for the new industrial paradigm – the transition from the raw materials orientation of the Russian economy to the innovative way.

Enhancing the transformation processes of the international labor division in the framework of neo-industrialization (Industry 4.0) poses a threat to the macroeconomic stability, including by reducing the competitiveness of domestic coal mining enterprises [2, 3]. The main uncertainty lies in the difficulties of forecasting the final form of equilibrium in international markets, due to the lagging behind the emerging and more competitive ‘technotronic society’ (when the equipment begins to operate the equipment). Neo-industrialization should also be considered as a scenario of transition to a sustainable development, which lies in coordination of efforts aimed at synchronizing the processes of industrialization and informatization of coal mines [4]. The compulsory elements of “sustainable development” (in the area of environmentalization of mining production and integrated development of the subsoil resources) include the provision of a productive environment, the transition to a low-carbon economy, and a set of energy saving and recycling measures [5-7].

The need to upgrade geotechnologies for the transformation of the energy sector within the framework of the green and ecological economies concept is indicated by the existence of national programs implemented in developed countries. The United States Department of Energy is
implementing this direction in the form of a system of initiatives (for example, the Clean Coal Technology and the Clean Coal Power Initiative). Of the most significant steps in this direction, it is worth noting the message of the European Commission “Sustainable power generation from fossil fuels: aiming for near-zero emissions from coal after 2020”.

The mining of coal- and gas-bearing beds by high-loaded longwall faces causes difficulties in ensuring the safety of drainage boreholes, as well as the problems of ensuring the required quality of the bypassing gas-air mixture for cogeneration purposes [8, 9]. The lack of reliability of the circuit drainage network can lead to the impossibility of using coal mine methane as fuel for gas engine generators of cogeneration units [10]. This brings up to date the need to develop a comprehensive program in the field of achieving environmental transformation and improving energy efficiency of mining production.

The environmental orientation of mining production is constrained by the lack of a rational vision of methane, not only as a greenhouse gas, but also a hidden potential able to increase the profitability of coal mining. The use of methane as an alternative energy carrier (in modular gas engine generators (GEG)) allows you to stream the generated electricity to the mine’s power system, simultaneously reducing the production cost.

Therefore, the purpose of the paper is to ensure the sustainable development of geotechnologies by identifying the spatial distribution of the circuit drainage network failures, using coal mine methane in cogeneration units.

2. Materials and methods

The work [11] described the existence of a non-linear nature of methane concentration dynamics in worked up degassing boreholes when developing a deep-lying (over 1300m) rich gas-bearing bed (methane content 19-23 m³/t daf) at Zasyadko Mine. The authors have found out that the cyclical nature of dynamics changes in the methane concentration in equally oriented boreholes (with taper angle to the bottomhole = 35° and angle of elevation to the horizon = 40°) is evident 50m in front of the longwall face.

The disadvantage of the study was the lack of clarity in the representation of the spatial and temporal nature of the methane emission flow, which restricts localizing the shape of areas with a dangerously low concentration of methane. Therefore, the work's data [11] were used as primary information for constructing the surface (based on the methodology [12]), reflecting the change in methane concentration in this type of boreholes depending on the distance from the coal face line and the slots position relative to the distance to the beginning of the site (the value of which are interrelated with different measurement times).

In contrast to LOESS (local polynomial regression) used in [13] for data smoothing, we applied the method of non-uniform rational B-splines. NURBS is a distance-weighted B-spline. Order in the x and y dimensions were equal – bicubic (order 3/3). NURBS was calculated only for nodes in data, further interpolation was carried out using conventional B-spline methods.

3. Spatial distribution of failures of "drainage holes" as an element of the circuit drainage network (according to the nature of the manifestation)

Due to the fact that the lower margin of the working range of methane concentration required for GEG's basic operation is 25-30%, an increase of the nonproductive (with a concentration of less than 25%) consumption of the mixture in the circuit degassing network poses a significant threat to the normal energy generation. From the theory of reliability it is known that the “failure” of the system is an event, accompanied by the loss of its operational state. From the point of view of reliability engineering, the state of the degassing system as a whole (the network or its elements) in which the concentration of methane in the bypassing mixture exceeds 25% can be considered “efficient”. Therefore, it is vital to hunt down the zones in which failures or, on the contrary, the operational state of the drainage boreholes can be traced.

The projection of the resulting surface on the S-L axis (the length of the air roadway of the
“pickets” of the 18th eastern lava – the distance from the longwall face to the coal face line) is shown in Figure 1.

![Figure 1](image)

**Figure 1.** The projection of the time variation of methane concentration depending on \( L \) (distance relative to the unmined coal) and \( S \) (distance to the beginning of the mine section) in the boreholes of the circuit drainage network: a) – zones of local minimum of methane release ("borehole failures"); b) – zones of local maximum of methane release ("usable condition of boreholes").

Figure 1 more clearly shows the movement of areas with cyclical changes in the dynamics of methane concentration. The dotted line denotes the line of the “zero” distance to the face (negative values are the distance ahead of the longwall), and the contour line represent the locus of points with the same methane concentration values. From the analysis of contour lines, it is obvious that most of the time when the holes are ahead of the longwall (more than 10m ahead of the lava), their work is characterized by insufficient reliability. Besides, it should be noted that the value and position of local maximum and minimum also non-linearly change their position in the S-L plane. As indicated in [6], apparently, "this process is greatly influenced by the size of the roof span and the distance to the longwall". Moreover, up to approximately 1335m from the beginning of the section (roof span = 25m), the area of the local maximum of methane release at a distance of 30m from the longwall (area b) began to move closer to the longwall, gradually changing to zones of local minimum. Local maxima on surface of the investigated function were traced at the following distance from the longwall: 1)-th (33% \( \text{CH}_4 \)) – from -30 to -35m; 2)-th (16%) – from -58 to -77m; 3)-th (16%) – from -110 to -120m. The minima of the "zone b)" function are traced: 1)-th – from -30 to -70m; 2)-th – from -35 to -45m. It should be clarified that the movement of the production face line was carried out in reverse. That is, conditionally from the picket 1360m (from the beginning of the panel), therefore, already at the picket 1350 m, the span of the main roof was 10m. In this regard, \( L = 40m \) (the length of goaf) was formed by the time when the face was on \( S = 1320m \). By the same time, we observe the beginning of the formation of the 1)-th minimum at -35m (ahead of longwall) - "zone a)".

Analysis of Figure 1 it follows that for the entire period of increasing the roof span to 80m (with a change in \( S \) from 1360 to 1280m), ahead of the face (\( L \) from -35 to -120m), a dangerously low concentration of methane in the extracted mixture can be traced. At the same time, operational control (blocking the channels of boreholes at their mouths) of the system's operation, apparently, was not
performed. The next feature is that with the formation of a sufficient roof span (40m and more), due to an increase in the reference pressure, a stable pattern of parallel stripes of isogas up to 24m in front of the lava is traced. Moreover, the parallel lines are directed at a certain angle to the axis L = 0. Isogas 25% with a span of 40m (corresponding to S = 1320m) is located only 10 m ahead of the face (L = -10m). At the same time, at S = 1280m, this distance increases to L = -20m.

Perhaps this is due to the squeezing out of the edge zone of the reservoir and the redistribution of part of the rock pressure deep into the massif. Indirectly, the revealed features confirm the results of foreign studies in the conditions of mines in China [14] (surveys of the state of underground wells), the data of laboratory experiments [15], as well as the conclusions of domestic studies [6].

4. Conclusion
Based on the obtained results, we can conclude:
- that the nonlinear nature of the dynamics of methane release is realized in the form of cyclical changes (alternation of minimum and maximum) of methane concentration in local areas of the rock mass that move relative to the coal face under the influence of changes in the geomechanical conditions of the excavation site;
- an increase in the span of the main roof from 11m to 66m is accompanied by an increase in the area of distribution of the zone of maximum methane emission at a distance of 70-90m in front of the face, but it is still insufficient to achieve a safe level of methane concentration in the degassing network;
- when mining high-methane-bearing seams of Donbass (at depths over 1000m), the inclusion of separate wells in the operation of the degassing network does not ensure the reliability of their operation until the face of the face approaches 40m.

Based on the theory of sustainable development, in our opinion, the essence of the environmental transformation of geotechnologies should lie in developing a set of measures based on a balanced interaction of society and natural biosystems, while reducing the emission of harmful substances (primarily mine methane) from air workings.

In order to significantly reduce mine methane emissions, it is necessary to monitor (in real time) the state of the degassing system. Based on the studies carried out, in most of the operation time (L from -120 to -20m), in front of the working face, an air-gas mixture with a methane concentration of 25% is discharged. This makes it necessary to create a network of sensors combined with shut-off valves at wellhead of each underground borehole. Obtaining the ability to quickly shut off ineffective wells will allow implementing the concepts of neo-industrialization of mining.

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