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UNDERGROUND MINING OF MULTIPLE COAL SEAMS: PROBLEMS AND SOLUTIONS

The foreign and Russian practices of mining of closely spaced coal seams are reviewed. The outcomes of the research accomplished by the USA National Institute for Occupational Safety and Health are generalized. It is found which geological and geotechnical factors govern safety and efficiency of mining of closely spaced coal seams. It is shown that the majority of accidents are connected with the influence of high stress zones generated by coal pillars left between longwalls. Methods to ensure stability of longwalls, assembling and disassembling chambers in mining of closely spaced coal seams in USA are described. The emergency situations due to destruction of longwalls in the influence zones of high stresses generated by pillars left in the upper seams are analyzed. For validation of the layout of underground excavations, in terms of Kirov Mine and using the Guidelines on Rock Bolt Support Design and Application in Coal Mines in Russia, the values of roof subsidence are calculated and plotted for different layouts of excavations with rock bolt support. Numerical investigation of stress state of overmined rock mass is presented for the conditions of Kirov Mine. It is shown that the most hazardous situation takes place when it is required to ensure safety of longwalling in the lower lying seam under the joint influence of previously mined out longwall and pillar in the upper lying seam. It is concluded on possible arrangement of longwall in the zone of high stresses in Kirov Mine, and it is recommended to shift headings beyond the high stress zone influence. Also, recommendations are given on economically efficient and safe mining of closely spaced coal seams. The areas of the further research are specified.

***Key words:** underground mining, multiple seams, longwall, undermining, overmining, interaction, ground control, gob solid, pillar.*
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Introduction

The international practice of mining assumes strata as closely spaced when they occur at a spacing of less than 60 m. Mining of such seams is characterized by the presence of one of the four principal modes of influence exerted by closely spaced strata: overmining, undermining, dynamic effect, effect of extremely closely spaced strata [1]. In mining of closely spaced strata, their interaction may result in inducing of various emergencies connected with mine support damage, roof falls and floor buckling. It is noteworthy that all coal mining countries are faced with the challenge of multiple seam mining [2, 5, 15]. This problem is of the current concern for Russian mines where accidents due to effect of earlier mined closely spaced strata [8, 10] entail essential economic disbenefits, and where the ground conditions in one of the basic coal fields—Kuzbass—is characterized by multiple seams. The issue of mining of closely spaced coal seams exists also in China where a package of studies has recently been undertaken to analyze interaction of closely spaced seams [15–17], including mine observations, physical simulation under laboratory conditions and numerical investigations. Considerable research was accomplished by the National Institute for Occupational Safety & Health—NIOSH in USA. The research was based on the empirical approach and consisted in generation and study of data bases on incidents of interaction of closely spaced seams [2].

This research objective was enhancement of economic efficiency and safety of underground mining of closely spaced coal seams.

The research method

The research method was the integrated approach, including the analyses of international experience gained in mining of closely spaced coal seams, studies of influence of various geological and geotechnical factors, review of procedures on determination of parameters of high stress zones in the course of mining of multiple seams, geomechanical modeling and numerical investigations, as well as the analyses of current solutions on mine layouts to ensure efficient and safe mining.

In the research period, the scope of the analyses covered accidents that took place in mining of closely spaced coal seams in USA [1–7] and in Russia [8–12]. The data base on such events generated by NIOSH (USA) consisted of 344 cases from 36 coal mines, including 252 cases of coal preparation and 92 cases of coal extraction [2].

For Russian mines, interaction of closely spaced seams is also of high concern. As a representative example, accidents that took place in Kirov Mine in 2009–2013, in the course of extraction of coal reserves from Polenovsky seam, in the high stress zones induced by pillars of the earlier mined upper lying seam Boldyrevsky were studied [8–11].

It should be mentioned that although Russia has a lot of regulatory documents that account for the influence of early mined seams, each of the documents considers only one aspect of such influence, and it is difficult to use jointly such documents in view of the different approaches to assessing parameters of the influence zones and due to some inaccuracies present [12]. The main documents on the assessment of influence exerted by closely spaced coal seams on the displacements of rocks in the roof, floor and side walls in mines include the Guidelines on Efficient Layout, Protection and Support of Coal Mines [13] and the Guidelines on Rock Bolt Support Design and Application in Coal Mines in Russia [14]. For the assessment of influence of overmining in the conditions of Kirov Mine and for validation of sites chosen to arrange underground excavations using the Guidelines on Rock Bolt Support Design and Application in Coal Mines in Russia [14], roof subsidence was calculated for different layouts of excavations with the rock bolt support.

Also in terms of Kirov Mine, geomechanical modeling was performed with ANSYS package, and stress state of rock mass was estimated in different geotechnical situations: under the effect of zone of high stresses in the area along the edges of a seam, under the influence of high stress zone due to a pillar, under the joint impact of the abutment pressure zone due to actual mining and the high stress zone induced by a pillar in the earlier mined seam.

Results of the research

The distribution of all case studies [2] relative to effective and hazardous influence of closely spaced seams in undermining and overmining with room-and-pillar method and with longwalling is shown in the **Fig. 1**. It is seen that more than half cases in the data base are drivage meant for preparation of coal for overmining (n = 190). Furthermore, under conditions of overmining in the edge area of coal seams, 90% of the considered cases are efficient. The rate of emergencies almost doubles (grows from 10% to 19%) in case of overmining in the presence of pillars in the mined-out void. Efficient undermining was implemented in 73% of cases of operation above edge areas of coal and in only 59% of cases in operation above pillars [2].

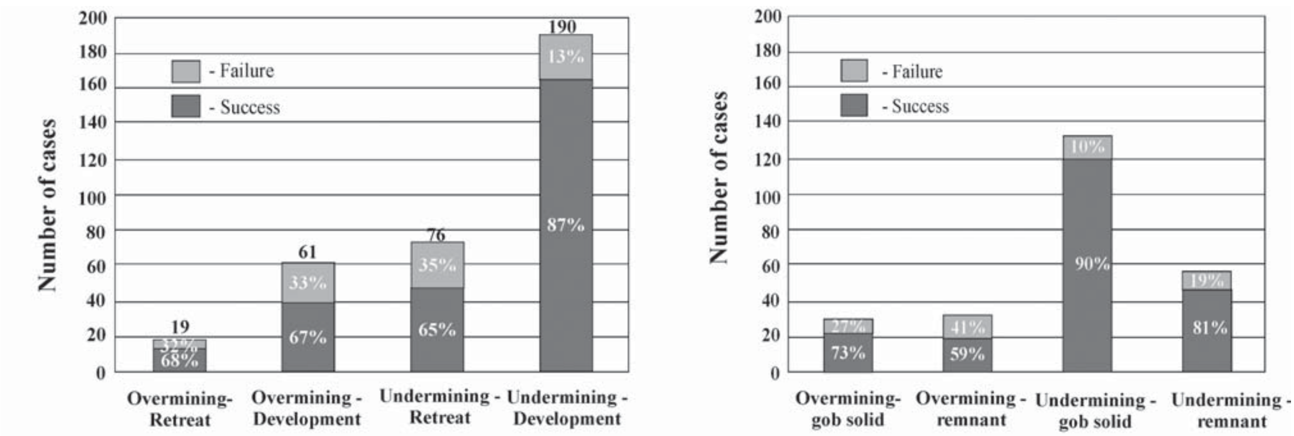
Figure depicts distribution of efficient and hazardous mining depending on the mining depth and the thickness of an interburden between the closely spaced seams. The depth of mining varies from 120 to 300 m in round of 90% of the cases analyzed. The interburden is thinner than 66 m, except for 20 efficient cases with the interburden of 110 m [2].

Fig. 2 illustrates interaction of closely spaced seams as against mining depth and interburden of seams in case of undermining. As is seen in **Fig. 2**, an increase in the interburden thickness over 60 m ensures efficient mining.

Numerical studies of geomechanical models constructed for the conditions of Kirov Mine allowed calculation of stress state of rocks. **Fig. 3** shows the fields of the vertical stresses calculated for the plane parallel to production faces to estimate parameters of high stress zones in different geotechnical situations such as:

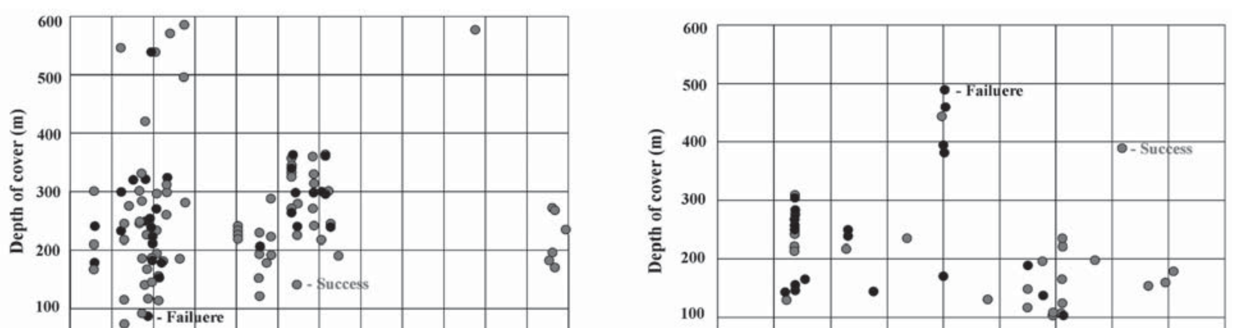
1) generation of high stress zone under superimposition of overmining-induced high stresses (pillar between longwall panels on Boldyrevsky seam) and actual mining-induced stresses in Polenovsky seam;

2) development heading in Polenovsky seam in the zone of extraction-induced high stresses;



a *b*

Fig. 1. Interaction of closely spaced coal seams: *a* — relative to direction and method of mining; *b* — relative to mine element (pillar or edge area); the bar charts are plotted based on the data from [2]



a *b*

Fig. 2. Efficient mining and accidents versus different depths and interburden thickness in case of multiple seams: *a* — overmining; *b* — undermining; the bar charts are plotted based on the data from [2]

3) high stress zone generated by edge area of Boldyrevsky seam.

It follows from **Fig. 3** that stresses in the high stress zone and dimensions of these zones are essentially different in different geotechnical situations, which should be taken into account when recommending on stable development heading in high stress zones in Polenovsky seam. The research shows that the most complicated case is geotechnical situation 1 in **Fig. 3**, which is characterized by overlapping of the high stress zone generated by a pillar in the previously mined seam and the abutment pressure zone created by the edge area in the seam under current mining. For this geotechnical situation, using the regulatory document in force [14], the roof subsidence is predicted and plotted for different arrangements of a room relative to a pillar (refer to **Fig. 4**), where curves and *1* and *2* show the calculated subsidence outside and inside the influence zone of mining, respectively. From the evidence of **Fig. 4**, the calculated subsidence even outside the influence zone of mining exceeds the limit values (300 mm) for rock bolt support if the room is arranged under or closely to the pillar in the contiguous seam. The situation is even worse inside the influence zone of mining as hazardous subsidence embraces the span longer than 100 m in Polenovsky seam in this case.

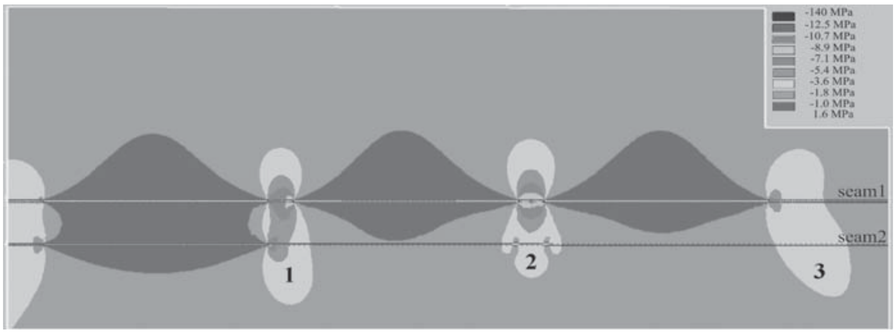


Fig. 3. Zones of high stress and destressing during mining of Boldyrevsky seam (vertical stress field)

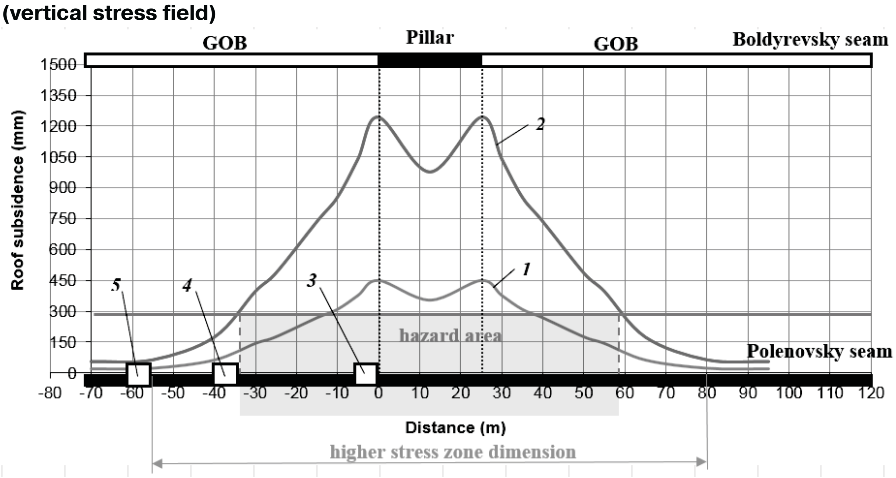


Fig. 4. Subsidence versus arrangement of an excavation in high stress zone

It is noteworthy that longwall planning practice based on experience of mining of multiple seams in USA mainly follows the recommendations presented below. In planning layouts of development drives in case of overmining, the mine excavations in the panel are shifted beneath the gob while pillars between the excavations are set wider, at the reduced number of cross headings under the edge area of rock mass [1]. At the same time, rational layouts of mine excavations in USA for many years recommended that excavations in closely spaced seams should be arranged one under the other [1], and such patterns are yet in use in some mines in USA [2, 5].

Assembling and disassembling chambers should be arranged under the gob of the contiguous seam and shifted by 30 m off the edge area of rock mass. The value of such shift was found experimentally, after the earlier recommendation on the shift of 13 m ended with an emergency [1].

Kirov Mine, SUEK-Kuzbass, continued longwalling with the development drives shifted by approximately 30 m under the gob relative to the excavation in the overlying seam, which ensured serviceability of the development drives within their life span [8].

Discussion of the results

The performed analysis of mining practice in closely spaced seams allows drawing a conclusion that the solution to the problem on mine support in high stress zones is provided by the arrangement of excavations under the gob, i.e. beyond the influence zone of high stresses, or in the zone of low stresses. At the same time, the actual geotechnical situations show that there are many factors capable to complicate consistency of mining. Currently Russia carries out mining operations in accordance with the principles of complete extraction of mineral reserves (as per the standards of the Governmental Committee on Mineral Reserves) but has to leave some reserves underground in order to ensure safety and efficiency of mining as there are no regulatory documents and science-based recommendations on coordination of operations in closely spaced seams.

It is inappropriate to use relations obtained based on the analyses of USA mines in the conditions of Russian mines as the analyses were performed regardless the mining system, schemes and parameters customary in Russia. In the meanwhile, the basic technology of underground coal mining in Russia is longwalling, while only 50% of USA mines use this technology. Furthermore, the analyzed data base on USA mines [2] includes mainly cases that took place at the depth down to 300 m below surface, when Russian mines are going to carry out deeper level mining in the nearest future, which will entail an increase in parameters of high stress zones, the other conditions being the same.

It is possible to eliminate mutual effect of closely spaced seams by shifting preparation and actual mining in space and time. However, the shift in time, recommended by the present authors in order to eliminated negative effects, is to be 7 to 15–20 years, which is impractible in high-rate mining in the comparatively space-limited areas of contiguous seams using heavy-duty heading machinery. The analyses of the real-time geotechnical situations show that current mining operations are carried out at the time shift of 2–5 years.

Another issue of coordination of mining in closely spaced seams is the consequences of the trend of the recent decade towards the increased lengths of longwalls and extraction panels. For instance, in USA the average lengths of an extraction panel and a longwall were 2650 m and 250 m in 2004 and 3558 m and 359 m in 2014, respectively, in accordance with [4]. The same situation exists in recent decade in Russia where the largest mines have increased the lengths of longwalls from 200 m to 300 m and the lengths of extraction panels from 2000 m to 3000 m and more. The available recommendations on arrangement of assembling and disassembling chambers as well as development drives in the influence zone of a contiguous seam reduce, as a rule, to shifting these excavations under the gob by the value of the order of 30 m. However, under conditions of the increased lengths and widths of extraction panels nearly by 1.5 times, it is impossible to implement the recommendations in terms of rock mass edge areas or gobs as the size of the newly prepared panels considerably exceeds the size of the previously mined-out panels in the closely spaced seams.

Conclusion

The problem of efficient and safe mining in the conditions of influence exerted by interaction of closely spaced seams is complicated by the joint effect of numerous factors that govern intensity of this influence. The main geological (natural) factors include: depth of mining, thickness of interburden, properties of rocks composing the interburden, properties of enclosing rock mass. These factors govern both the conditions of mining and the rate of interaction of closely space seams. The geotechnical factors to influence mining efficiency in closely spaced seams are: applied method of preparation and system of mining, presence of stable coal pillars, time lag between mining operations in the seams.

The main cause of accidents in the course of mining of multiple seams is generated by coal pillars left between longwall panels and initiating formation of zones of high stresses in the seams. Longwalling with unmined coal pillars is currently the basic mining system in Russia (making to 90% of the overall underground production of coal). Wide application of this system of mining is conditioned by the use of modern heavy-duty cutting–loading machinery. Unmined pillars are left as the basic support of a mine, which allows low labor content and cost of support installation and ensures high rates of heading. Thus, mining of closely spaced coal seams in Russia in the nearest future is connected with the operation in high stress zones generated by pillars left in the previously mined seams, which enhances immediacy of the subject of this research.

The most challenging in the longwall mining is support of development headings in the influence zone of mining, where contiguous seams generate high stress zone, which is confirmed by many researchers [6, 8, 11]. The studies preformed for the conditions of Kirov Mine allow a conclusion that negative impact of high stress zones can be eliminated by mine planning so that development headings are shifted beyond the limits of the said zones. According to the related studies, the use of the modern powered support in a longwall enables efficient operation even inside the zones of high stresses [10].

Another difficulty to rational mine planning and layout in case of closely spaced seams is presented by the fact that parameters of extraction have grown in recent decade (lengths of longwalls and panels). So, it is hard to arrange development headings so that they occur beyond the high stress zones when closely spaced seams are mined out with a considerable time gap.

The further research towards improvement of safety and efficiency of mining of multiple seams includes the following areas of concern:

- Procedures and approaches to determining rational layout for headings, assembling and disassembling chamber under various ground and geotechnical conditions;
- Compliance of coal pillars and development of process flow charts for extraction of coal reserves from pillars between longwalls so that to eliminate origination of high stress zones in closely spaced seams;
- Effect of time factor on change in stresses and strains in rock mass in the influence zones of mining;
- Principles of concurrent mining of closely spaced coal seams so that mining operations are coordinated in space and time.

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ENERGY-EFFICIENT TECHNOLOGIES OF INTERGATED COAL AND MINING WASTE DEVELOPMENT IN THE MOSCOW COAL BASIN IN THE CONTEXT OF SECURE AND SUSTAINABLE SUPPLY OF RAW MATERIALS IN CENTRAL RUSSIA

A conceptual framework is provided for high-technology and energy-efficient production of nanomaterials and rare earths toward import substitution and technological independence of machine engineering and other industries in the central region of Russia. It is shown that there are prerequisites for meeting this challenge based on innovative technologies of integrated development of coal deposits and mining waste in the territory of the Moscow Coal Basin. A solution to the problem is an integrated approach to study and development of geotechnologies for high-level processing of coal and production waste based on underground gasification of lignite via filtration channels and a chemical geotechnology for extraction of useful components from ash residue recovered from underground mined-out area. The proposed approach is intended to create a background for implementation of projects fostering regional safety enhancement, primarily, in the field of mineral mining and in technosphere, and, later on, in the socio-economic environment.

Key words: *integrated coal mining, coal, mining and processing waste, underground coal gasification, energy efficiency nanomaterials, rare earths, Moscow Coal Basin, Tula Region.*

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Introduction

Science-based evaluation and high-tech and energy-efficient production of nanomaterials and rare metals towards sustainable import substitution and technological independence of machine building and other industry branches in Central Russia is one of the most critical challenges of this time. The analysis of mineral supplies base and the current technologies shows that meeting the challenge is possible based on innovative techniques of integrated development of coal reserves and mining waste in the Moscow Coal Basin [1–4]. At the same time, the modern approaches described in the new global research [18] devoted to the holistic view over the energy feedstock supply chains reveal the economic, political and social concern about technological efficiency of energy feedstock production and utilization, especially when it becomes increasingly difficult to get access to energy minerals [19]. In this connection, the relevance of R&D discussed in this article is "in flow" of the global trend toward regional security, including mineral resources and energy supply. The issue of secure and sustainable supply of raw materials in general and, specifically, in terms of coal supply in Russia is studied in detail in [23, 24].