UDC 622.273.3:622.285

S. A. PROKOPENKO [1], *Doctor of Engineering Sciences, Professor, sibgp@mail.ru*
V. V. SEMENTSOV [2], *Head of Laboratory of Geomechanics in Mining, Candidate of Engineering Sciences*
M. S. DOBROVOLSKY [2], *Senior Researcher*
E. V. NIFANOV [2], *Researcher at Laboratory of Geomechanics in Mining*

[1] *Tomsk Polytechnic University, Tomsk, Russia*
[2] *Science Center VostNII, Kemerovo, Russia*

CLASSIFICATION OF PROTECTIVE PILLARS TOWARD HIGHER SAFETY AND INNOVATION IN ROOM-AND-PILLAR COAL MINING

During room-and-pillar mining, protective pillars of coal are usually left standing. The protective pillars differ in shape, size, process properties and extractability ratios of coal. The authors propose a classification of the protective pillars with respect to their structure and shape in order to estimate and predict their properties. The extractability ratios of coal are calculated for the initial rib pillars and panels at different final shapes of protective pillars. The protective pillars are ranked with respects to the coal extractability ratios. Such systematization of pillars enables selecting the best engineering solutions and innovative improvement of room-and-pillar mining in specific geological conditions toward enhanced safety and efficiency of underground coal production.

Keywords: *mine, room-and-pillar mining, rib pillar, protective pillar, cut, cutter–loader, extractability ratio, losses, classification, shape.*
DOI: *10.17580/em.2020.02.06*

Introduction

In Russia rock-and-pillar mining operations used and are using various flowcharts described in many domestic papers, dissertations and R&D reports [1–5]. Mineral reserves from pillars are extracted by various width and length cuts [6]. Mining safety is ensured by narrow pillars established between the cuts and named as protective pillars [7]. These pillars are meant for temporary roof support to prevent roof falls in the working area. Different parameters of pillars and rooms, productive entries, their sequences and directions result in formation of coal pillars of various shapes, sizes and behavior. As a consequence, we have different volumes and extractability of coal reserves left in the pillars, different life times of the pillars, different air conditions in mining area, which, in the long run, governs efficiency and safety of coal production. This paper is aimed to generalize and classify protective pillars in order to assess their safety and to predict coal extractability ratio of room-and-pillar mining. These objectives are of concern both in project planning and in management in coal mining.

Flowcharts of coal extraction from rib pillars

Mines operating in the Kuznetsk Coal Basin (Kuzbass) in Russia are the most experienced in room-and-pillar mining. For the past 20 years, these mines have developed and used more than ten flowcharts and modifications [8, 9]. The basic parameters of the room-and-pillar mining technology (width and length of rooms and rib pillars) are most strongly influenced by the thickness, structure and strength of coal and overburden; susceptibility of coal to dynamic events and spontaneous ignition; structural parameters of equipment.

Differences between room-and-pillar flowcharts become observable in the phase of extraction of coal reserves from rib pillars. These pillars are left intact when mining is carried out under guarded objects on ground surface, or in very thick coal seams. In these cases, coal losses can reach 60–75% [8].

It is possible to reduce coal loss using flowcharts with partial extraction of coal reserves from the pillars by cutting at an offset from the room boundaries and with induced roof caving. Extraction of coal reserves from rib pillars by single-way through cuts and with establishment of narrow protective pillars (to 3–4 m wide) increases coal extractability. On the other hand, in coal seams susceptible to spontaneous ignition, it is required to drive blind cuts, which decreases air inlet in mined-out area and reduces the likelihood of endogenous fires but diminishes extractability ratio of coal. Extraction of coal reserves from pillars by cuts made on both sides of a pillar (a fur tree flowchart) diminishes the amount of shunting in roadways and enhances coal production.

In simpler geological conditions (Tyva, Neryungri) as against Kuzbass, protective pillars have smaller width of 1–2 m. This allows excavating the full thickness of coal seams, in single pass and at smaller cost of roof support. Extractability ratio reaches 60–65% in this case [8].

In foreign mines, coal reserves are extracted from rib pillars using mobile electrohydraulically controlled roof support [10–14]. These support systems are placed at junctions of rooms and cuts in the pillars and are advanced after a cutter–loader. Step-wise arranged two or three roof support systems push away the natural roof caving zone from the operation zone of a cutter–loader and allows safe conditions for extraction of coal from pillars [15, 16].

Coal extraction from long pillars is carried out using mobile roof support and one-side or two-side retreat mining flowcharts with roof caving in mined-out void. Square pillars are cut on four or two sides, with establishment of coal pillars of minimum size. Diagonal parallel or cross cuts are driven as well [17].

Mobile roof support has been used in the leading coal mining countries for three decades, with various flowcharts of coal extraction from pillars. The experience gained has proved efficiency of the machines. Moreover, extractability ratio of coal is increased to 90% at enhanced safety and productiveness of mining [18].

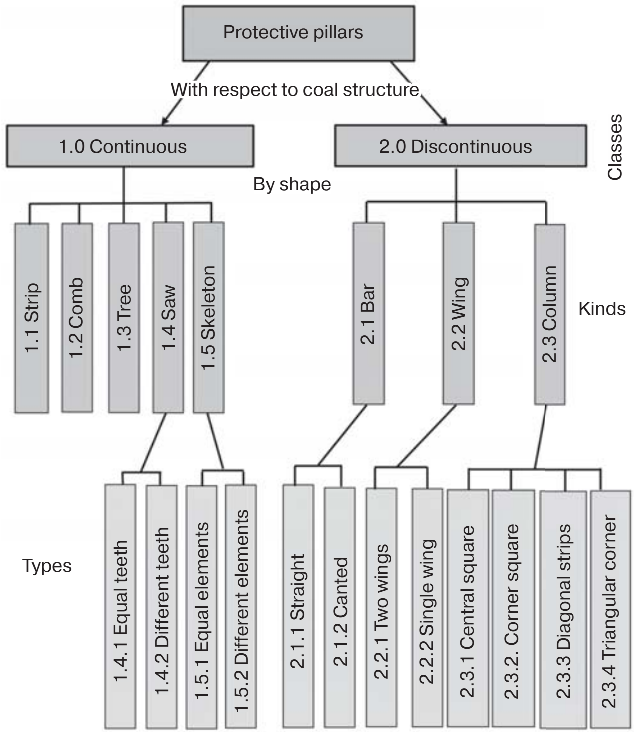


Fig. 1. Classification of protective coal pillars

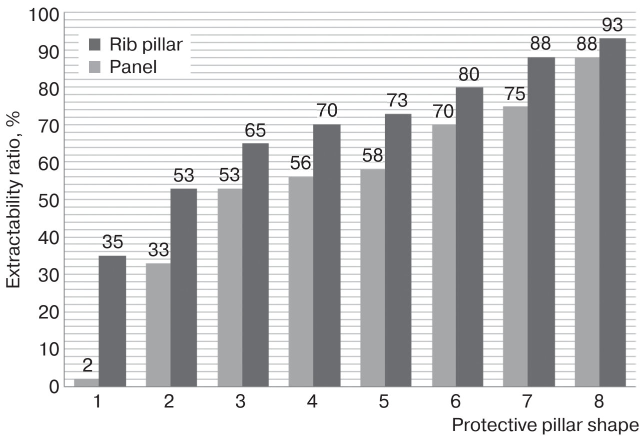


Fig. 2. Ranks of protective pillars in terms of coal extractability ratios and shapes:
1 — strips; 2 — combs; 3 — bars; 4 — skeletons; 5 — wings; 6 — columns; 7 — trees; 8 — saws

Extraction of coal from narrow protective pillars

All rib pillars in room-and-pillar mining initially represent coal prisms bounded by rooms as well as by overlying and underlying rock strata. The prisms are laterally elongated as their length is much more than width. The prisms can also be shaped as columns of equal sizes in plan view.

As mining is advanced, the rib pillars acquire various and often unordinary shapes due to different flowcharts used. The variety of shapes, sizes and behavior patterns of protective pillars can be grouped into two classes with respect to their structure: continuous (1.0) and discontinuous (2.0) (**Fig. 1**).

In the continuous pillars, initial coal mass is integer along the length of the prisms. Brattices installed in drifts allow isolation of mined-out areas, which is important for aerodynamic control in a working area. The studies distinguish between five continuous shapes of pillars: strip-shaped (1.1), comb-shaped (1.2), tree-shaped (1.3), saw-shaped (1.4) and skeleton-shaped (1.5). The discontinuous pillars have detached elements due to through passes of cutter–loaders in the pillars. The final elements can be shaped as straight bars (2.1.1) or canted bars (2.1.2), wings (2.2.1 and 2.2.2) or columns (2.3.1–2.3.4).

Descriptions of different-shape protective pillars are compiled in **Table**.

The classification of the protective pillars helps estimate and predict their air permeability, load-carrying capacity, stability, and extractability ratios of initial rib pillars and panels.

The room-and-pillar mining process brings coal pillars in different conditions: initial, high-load, critical, failure. The rate of change in the pillar conditions under the same loading depends on the mining technology and strength of the roof and floor rocks. The shapes and characteristics of coal pillars in Table 1 are valid for the establishment moment of the pillars. Time to failure of the protective pillars ranges from a few weeks and months (strips, columns, staggered pillars) to a few days and hours (bars, tree shapes). The saw-shaped pillars feature the lowest stability. The peripherally saw-like walls stand from 1–h to 30–40 min after cutter–loader leaves the cut [19].

Estimation of coal extractability ratio

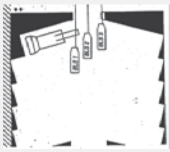
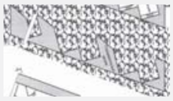
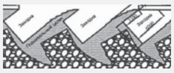
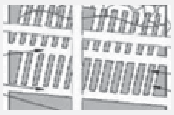
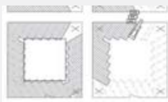
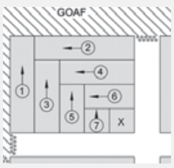
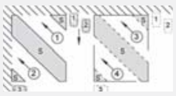
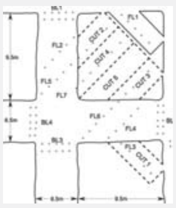
At the same sizes of initial rib pillars, different flowcharts of coal extraction from the pillars result in formation of different shape protective pillars and, accordingly, in different extractability ratios of coal. The highest extractability ratios are the characteristics of tree-shaped and saw-shaped protective pillars (1.3 and 1.4). Such pillars represent remnant narrow walls of coal in the center or in the periphery of the initial rib pillars. The extractability ratio of coal in case of a tree-shaper protective pillar reaches 70–80% in the rib pillar and 85–90% in the panel.

In case of the saw-shaped pillars with equal size teeth (1.4.1), coal extractability ratio reaches 85–90% in the rib pillar and 90–95% in the panel. In case of the saw protective pillars with different teeth (1.4.2), coal extractability ratio is 58% in the rib pillar and 80% in the panel. On average, the saw shape of protective pillars (1.4) ensures coal extractability of 77% and 90% in the initial rib pillars and in the panel, respectively.

A relatively high extractability ratio of coal is observed with column-shaped protective pillars (2.3): from 55 to 95% for the rib pillars and from 74 to 97% for the panels subject to the final shapes of the protective pillars (square 2.3.1 and 2.3.2, diagonal 2.3.3 and corner 2.3.4). The average extractability ratios with the column pillars (2.3) are 73% for the rib pillars and 83% for the panels.

High extractability ratios above are achievable owing to mobile roof support. Temporal transfer of load from strata pressure to the mobile support allows rapid extraction of coal from rib pillars nearby the support at minimized coal loss, and enables retreat removal of cutter–loaders from the zone of roof caving. These flowcharts provide the highest efficiency

Table 1. Shapes and characteristics of protective coal pillars

No.	Description	Final form	Shapes and types	Extractability of rib pillar, %	Extractability of panel, %
Class 1.0. Continuous pillars					
1	Elongated coal prism		1.1 Strip	0	30–40
2	Elongated prism with blind cuts		1.2 Comb	33	50–55
3	Central stepped wall with narrow partitions		1.3 Tree	70–80	85–90
4	Peripherally toothed wall		1.4.1 Saw with equal teeth	85–90	90–95
	Peripherally toothed wall		1.4.2 Saw with different teeth	58	80
5	Prism with asymmetric two-side cuts		1.5.1 Skeleton of equal elements	50–55	65–70
	Prism with asymmetric two-side cuts		1.5.2 Skeleton of different elements	64	76
Class 2.0. Discontinuous pillars					
6	Elongated prism with through passages		2.1.1; 2.1.2 Straight and canted bars	50–55	65
7	Discontinuous island		2.2.1 Two-winged	50	60
	Discontinuous half-island		2.2.2 One-winged	55–60	70–75
8	Tetragonal prism		2.3.1 Central square column	60–80	67–82
	Tetragonal prism		2.3.2 Square corner column	90–95	97
	Parallelogram and trigonal prisms		2.3.3 Diagonal column	55	74
	Trigonal prism		2.3.4 Triangular corner column	78	87

of room-and-pillar mining at the present day, minimize risk of accidents and maximize productivity.

The skeleton shapes with equal elements (1.5.1) and different elements (1.5.2) of protective pillars enable extractability ratios of 50–55–64% and 65–70–76% in the rib pillars and in the panels, respectively. The same level extractability is a feature of the wing-shaped pillars (2.2): 55 and 79% on average, respectively. In case of the bar-shaped pillars (2.1), extractability ratio of coal reaches 50–55% in the rib protective pillars and 65% in the panels.

When the protective pillars have a shape of strips (1.1), extractability ratio in the panel never exceeds 30–40%. On the other hand, the strip pillars feature high load-bearing capacity and ensure stable roof support for a long time. When blind cuts are made in a strip pillar, which transforms it to a comb pillar (1.2), the extractability ratio of coal rises to 30–35% in the rib pillar and to 50–55% in the panel. The extractability ratios are shown versus the pillar shapes in **Fig. 2**.

It is seen in Fig. 2 that the extractability ratio changes 2 times, from 33 to 77% as a function of the protective pillar shape. The difference in the extractability ratio of rib pillars and panels varies from 10 to 20% subject to the shapes and number of protective pillars in a panel.

The most effective shapes of protective pillars are saws (1.4), trees (1.3) and columns (2.3). The extractability ratios with such shapes range as 73–77% in the rib pillars and 83–90% in the panels. The wing-shaped (2.2), bar-shaped (2.1) and skeleton-shaped (1.5) protective pillars provide extractability ratios of coal from 50 to 58% in the initial rib pillars and from 60 to 73% in the panel. The least efficiency in terms of extractability ratio not higher than 33–53% is a feature of the comb-shaped and strip-shaped pillars (1.2 and 1.1, respectively).

Conclusions

The implemented research has revealed a variety of possible shapes, sizes and conditions of protective pillars. The proposed classification of protective pillars with respect to their structure and shape puts all protective pillars into two classes. The class of continuous pillars comprises five kinds and four types of pillar shape, while the class of discontinuous pillars embraces three kinds and eight types of pillar shapes. The estimation allows ranking protective pillars with respect to coal extractability ratio. The use of the classification allows predicting safety and efficiency of room-and-pillar mining at the stages of planning, implementation and innovative improvement of mining operations.

Acknowledgments

The article is prepared in the framework of the Competitiveness Enhancement Program of the Tomsk Polytechnic University.

References

1. Yakovlev D. V., Baskakov V. P., Rozembaum M. A., Kalinin S. I. On shortwall mining of bump hazardous coal beds. *Ugol*. 2015. No. 7. pp. 13–16.
2. Baskakov V. P., Rosenbaum M. A., Kalinin S. L., Sementsov V. V., Dobrovolskiy M. S. Thick seam mining unsafe gas-dynamic, system short working faces. *Ugol*. 2015. No. 11. pp. 17–20.
3. Cherepov A. A., Shiryaev S. N., Kulak V. Yu. Stress and strain distribution in geomass under room-and-pillar mining of a thick gently dipping coal bed. *GIAB*. 2017. No. 9. pp. 170–178.
4. Rockburst hazard analysis and recommended mitigation activities. Size optimization of rib pillars. R&D Report. Project Manager S. I. Kalinin. Prokopyevsk, 2015. 214 p.
5. Tatsienko V. P. Development and scientific substantiation of shortwall mining flowcharts for gently dipping and inclined coal seams in Kuzbass mines. *Synopsis of Doctor of Engineering Sciences Thesis*. Moscow, 2003. 42 p
6. Baskakov V. P., Igishev V. G., Sementsov V. V., Dobrovolskiy M. S. Insulation used chamber at coal mining system of short working faces. *Ugol*. 2016. No. 4. pp. 44–47.
7. Sementsov V. V., Dobrovolsky M. S., Nifanov E. V., Shabalin M. P. Application of the shortwall face system when developing coal seams prone to dynamic phenomena. *Vestnik NTS VostNII.* 2017. No. 2. pp. 27–31.
8. Sementsov V. V., Dobrovolskiy M. S., Nifanov E. V., Shabalin M. P., Prokopenko S. A. Investigation of the technologies for coal pillar extraction during room-and-pillar mining in russian mines. Review. *Vestnik NTS VostNII*. 2018. No. 4. pp. 5–23.
9. Prokopenko S. A., Ludzish V. S., Li A. A. Recycling possibilities for reducing waste from cutters on combined cutter-loaders and road builders. *Waste Management & Research.* 2017. Vol. 35(12). pp. 1278–1284. DOI: 10.1177/0734242X17731154
10. Prokopenko S. A., Sementsov V. V., Dobrovolsky M. S. Technology of extended pillar recovery in room and pillar mining in leading coal producing countries. Review. *Eurasian Mining*. 2019. No. 1. pp. 21–25. DOI: 10.17580/em.2019.01.05.
11. Wilson H. G. Mobile Roof Support for Retreat Mining. *Proceedings of 10th International Conference on Ground Control in Mining.* Morgantown, WV, June 10-12, 1991. Dept. of Min. Eng., WV Univ., 1991. pp. 103–114.
12. Lind G. H. Key success elements of coal pillar extraction in New South Wales. *The Journal of The South African Institute of Mining and Metallurgy*. 2002. pp. 199–205.
13. Mark C., Chase F. E. Analysis of retreat mining pillar stability (ARMPS). *Proceedings of Seminar on New Technology for Ground Control in Retreat Mining*. Pittsburgh. U.S. Bureau of Mines, 1997. pp. 17–34.
14. McTyer K., Sutherland T. The Duncan Method of Partial Pillar Extraction at Tasman Mine. *11th Underground Coal Operators' Conference.* University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2011. pp. 8–15.
15. Mark C., Zelanko, J. Sizing of final stumps for safer pillar extraction. *20th International Conference on Ground Control in Mining Morgantown*, Virginia, USA, August 2001. pp. 59–66.
16. Maleki H., Owens J., Endicott M. Field evaluation of mobile roof support technologies. *Proc. 20th International Conference on Ground Control in Mining*. Morgantown, WV. West Virginia University, 2001. pp. 67–77.
17. Galvin J. M. Pillar Extraction. Ground Engineering – Principles and Practices for Underground Coal Mining. Springer, Cham. 2016. pp. 309–358.
18. Howe L. A Decade of Mobile Roof Support Application in the United States. *Proceedings of 17th International Conference on Ground Control in Mining.* Morgantown, WV, August 4–6, 1998. Dept. of Mining Engineering, WV Univ. pp. 187–201.
19. Instructional guidelines on selection of geomechanical parameters of shortwall coal mining technology. Saint-Petersburg: Inter-Branch Science Center VNIMI, 2003. 53 p.