Extraction of Coal from Steeply Inclined Coal Seams, Using a Fully Mechanised Sublevel Caving Mining System in the Kazimierz-Juliusz Coal Mine

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Abstract

Mining of thick and steeply inclined hard coal deposits belongs to some of the most difficult engineering challenges. The Sublevel Caving system, originating from the ore mining industry, is one of the systems applied in such cases. That system has been used in coal mining for more than sixty years, although it became fully mechanised only at the beginning of the present century. The unique mechanical mining face mining method was applied for the first time in the Kazimierz-Juliusz Coal Mine in Poland to cut a deposit 20 m thick and inclined at more than 40°. The longwall protection system consisted of two mechanised support sets that were coordinated with the chain conveyor. The conveyor crossover was located on the spoil heap. Coal cutting was performed by blasting and coal was loaded gravitationally directly onto the conveyor. Using that mechanical system, a three-person strong face team obtained the output at the level of 600 to 1,000 Mg per day. About a dozen of years of experience gained in the Kazimierz-Juliusz Coal Mine allowed the engineers to improve the extraction process and reduce the face costs to the level of about 6 euros/Mg. Another essential achievement included elimination of serious accidents at the mining face. In addition to the process de-scription, this paper contains selected production results obtained upon the implementation of the sublevel caving system in the Kazimierz-Juliusz Coal Mine.

1. Introduction

The Kazimierz-Juliusz Coal Mine in Sosnowiec was operated continually from 1884 to 2015. During its operation period, the Coal Mine produced high-quality thermal coal. Starting in the 1990's, commercial coal was obtained from thick Seam 510. Coal was extracted at that level by the longwall system along strata, with caving and hydraulic backfill, in the areas where inclination did not exceed 30°. However, the resources became almost completely exhausted at the beginning of this century. The extraction of the remaining portion of Seam 510, inclined at 35 to 50°, became the subject of designs and tests conducted jointly by a research team from the Faculty of Mining and Geoengineering of AGH University of Science and Technology in Kraków and the Kazimierz-Juliusz Coal Mine engineers, with the intention to identify the most profitable and safe mining system. As a result of specific design works, two fully mechanised mining systems turned out to be interesting for the Coal Mine managers, selected from several technical proposals. In addition to the predicted low mining costs, the systems were characterised by low initial capital investment necessary for starting exploitation tests. Those systems were the following: the so-called Inclined Working system (a variety of the Cut and Fill system) and the Sublevel Caving system [1]. The Cut and Fill system was tested during more than twelve months and abandoned owing to low output and high mining-face costs. The Sublevel Caving system, being the object of this paper, was used continually from 2003 until the Coal Mine was closed in 2015. In that period, more than 12 million tons of coal was extracted from Seam 510 of Mine Section M-3.

2. Geological And Mining Conditions At Seam 510

Seam 510 of Mine Section M–3 was deposited in the form of a trough. The trough bottom was about 500 m deep, while the deposit outcrop was located at the depth of about 50 m in the trough wing. Mine Section M–3 was cut through and divided into northern and southern parts by a fault dropping from 25 to 40 m. The coal seam inclination in the southern part, where the sublevel caving system was implemented, amounted to 45° (Fig. 1). The seam thickness varied on that area, from 16 to more than 20 m. A number of faults occurred in the Mine Section, representing various drop and direction parameters. Fault drops changed from several to about a dozen of metres.

The roof of Seam 510, Mine Section M–3, contained intermittent layers of mudstone and sandy schist or shale, from 1.0 to 8.0 m thick. A sandstone layer was identified above, about 13 m thick. At the distance of ca. 45 m from the seam roof, there was another sandstone bar, ca. 40 m thick. Generally, intermittent layers of mudstone and sandy schist or shale occurred at the bottom of the coal seam.

The coal of Seam 510 was characterised by the average uniaxial compressive strength R_c of more than 20 MPa, with the maximum value exceeding 35 MPa. The compressive strength of sandstones occurring in the roof reached from 30 to more than 70 MPa. The roof mudstone displayed the strength from 20 to more than 30 MPa, while the strength of sandy schist reached from 30 to 40 MPa.

Seam 510 was assigned to Category I of methane hazard (in a 4-degree scale). However, the methane content of Seam 510 did not exceed $0.1 \text{ m}^3/\text{Mg}_{\text{CSW}}$ (0.1 m^3 of methane in one ton of dry and clean coal substance), on the area of sublevel caving operation. The coal from Seam 510 across the whole Coal Mine was included in Group V of ignition temperature (in the 5-degree scale of fire hazard), representing coal with a very high tendency to self-ignition. The self-ignition indicator of Mine Section M–3 coal was determined at 179°C/min., with the activation energy of 37 kJ/mol. The fire incubation time amounted to ca. 30 days.

The coal deposit level was assigned to Degree II of water hazard (in a 3-degree scale). The aquifer located within the sandstone, lying above Seam 510, was the main source of water hazard. Coal workings and cutting operations caused water dripping and local leaks. Increase inflow was observed at the final stage of mining, with small influx from Tertiary sands.

Seam 510 was assigned to Degrees I and II of rock-burst hazard (in a 3-degree scale). Coal mining by the sublevel caving method was carried out in accordance with the regimes specific for Degree III of rock-burst hazard, owing to the novelty nature of the mining method and the intention to ensure safety and obtain rock-mass data from the mining field. For that reason, the number of detectors (seismometers and geophones) was increased in the mining areas.

3. Sublevel Caving Mining Technology

Sublevel caving has been applied in thick and inclined deposit mining since the 1960's. The method was transferred from ore mining to coal mining. Mining consists in cutting and releasing coal shelves located above the mining longwall. In its traditional variation, also applied in ore mining, blasting boreholes are

drilled from the sublevel drift deep into the roof (usually in the fan arrangement), followed by explosive charging and blasting. The spoil is removed mechanically from the mining face [2, 3, 4]. Another method is based on hydro-cutting instead of blasting. Water is used in the cutting process for both coal cutting and transportation [5, 6, 7, 8]. There is also a third method consisting in the undercutting of the coal layer and causing a collapse, followed by gravitational release of spoil [9, 10]. Those methods were frequently applied in many countries, including Russia, France, Japan, Spain, former Yugoslavia, or Canada. Several methods, based on the technologies similar to sublevel caving, were developed in the second half of the 20th century. The most commonly used one until today is the French Soutirage method, as well as the Velenje method developed in former Yugoslavia. Those methods were mainly designed to mine the coal seams whose horizontal thickness exceeded 12 m. In both methods, mining was conducted within a short working, connecting two drifts: one below the roof and the other one at the seam bottom. The mining works within the working, protected by hydraulic stands or mechanical roof support, were conducted by either blasting or using a single-head shearer loader, up to 3 m high. The Soutirage method consisted in gravitational releasing of the undercut coal seam, from a 6–9 m high shelf [9, 10]. Under the Velenje method, coal cutting within a roof shelf up to 13 m high was performed with the application of long blasting boreholes, owing to coal hardness [11, 12, 13]. Gravitationally falling spoil was transported to the delivery drift by a conveyor.

3.1 General description of the sublevel caving system applied in the Kazimierz-Juliusz Coal Mine

High strength parameters of coal found at Seam 510 in the Kazimierz-Juliusz Coal Mine caused that it was necessary to apply blasting works in coal mining. Owing to changing coal seam thickness and extent, the Velenje method was not used. Instead, a typical sublevel caving system, with a single sublevel drift, was applied in each coal seam. Mining panels were designed by dividing Seam 510 into horizontal blocks, determined by the planes being perpendicular to roof and bottom. The blocks or mining panels were shaped as squares in cross-section, with a vertically situated diagonal. The square side length of the panel cross-section was close to the seam thickness in the given mining areas, i.e. usually from 16 to 24 m [1, 4]. The panel arrangement diagram in Seam 510 is shown in Fig. 2.

One working, called the sublevel drift, was cut out from the transportation ramp in each mining panel at particular mine levels. Such workings were cut out nearly horizontally, observing the direction of the seam extent at the seam's bottom, starting with the lowest mining panel. The drift was cut out from the transportation ramp to the field boundary in the given deposit wing.

Once the sublevel drift reached the assumed mining panel boundary and after the drift was fitted, mining was conducted by caving. The mining operations were continued by regularly repeated drilling of fan-shaped blasting borehole arrangement, explosive charging and blasting, gravitational spoil release and coal removal with conveyors and reloading systems in the sublevel drift.

Mining was completed at the run out once the stopping line was reached, usually at the protection pillar location designed for the transport ramp. The face equipment was relocated to the subsequent panel before the final liquidation of the previous panel by placing an insulation plug. The diagram of the sublevel caving system applied in the Kazimierz-Juliusz Coal Mine is presented in Fig. 3.

Particular engineering stages of the sublevel caving mining technology, applied at Seam 510 of the Kazimierz-Juliusz Coal Mine, are presented in detail in subsequent sections below.

3.2 Preparatory works

The connection of the mining and ventilation workings, within the coal seam inclined at 45° (with the difference in height of ca. 110 and 170 m), was performed by cutting a series of stepped ramps. Such ramps were composed of fairly short sections (usually ca. 60 m each), situated diagonally in respect of the coal seam extent, and with the inclination of 25° (Fig. 4).

Keeping of such an inclination of the stepped ramps allowed for cutting the workings with the harvester technology, using typical mining and delivery machines and equipment. Besides, maintaining the 25° inclination allowed for deliveries of materials, including heavy support systems, chain conveyor components, and steel stands, as well as coal delivery by conveyors. The ramps were placed under arched support made of V25 sections.

Sublevel drifts constituted the last link of the preparatory working arrangement designed for the sublevel caving system. Such workings were cut from stepped ramps, with a slight elevation of up to 5°, along the coal seam bottom, in the places determined by the field subdivision into particular mining panels (Fig. 2). The distances between the operating drifts depended on the coal seam thickness and they were usually similar to seam thickness, but not shorter than ca. 15 m.

Similarly to stepped-ramp cutting, the sublevel drifts were cut out by the harvester technology, using typical transportation machines and equipment. The sublevel drifts were executed with rectangular support, in compliance with the shape of the mechanised support set, used in the mining face at the stage of mining works. The diagram of the rectangular sublevel drift support is presented in Fig. 5.

3.3 Mining face equipment

The face of the sublevel drift was equipped with a system of three basic installations used for support, coal delivery, and borehole drilling as follows:

- Mechanised Support Set (MSS),
- Nowomag PZ–1000 chain conveyor,
- VPS–01 portable drilling machine.

In addition, the mining faces were equipped with such small tools as pneumatic hammers, pneumatic or hydraulic screwdrivers, pneumatic blasters, burst charge and clay wad devices, and other blasting equipment. The protection of working areas at the face was provided by the MSS system. The set was composed of two specially designed mechanised support sections whose main task was to protect the area against dropping rocks or uncontrolled relocation of spoil after the caving operation (Fig. 6). The respective locations of MSS and PZ–1000 sections are presented in Figs. 7 and 8. The PZ–1000 conveyor was used for the delivery of spoil released from roof, i.e. by gravitational loading, directly after charge blasting. The conveyor structure allowed for keeping the conveyor crossover within the collapse area at the length of ca. 5 m from the MSS protection system, facilitating transportation of spoil released in the caving area.

A Czech InterCupro VPS–01 hydraulic drilling machine was installed at the mining face. That device was designed for drilling small diameter blasting boreholes in coal and rock by the rotation method.

3.4 Coal cutting method

The mining technology based on the sublevel caving system design, applied in the Kazimierz-Juliusz Coal Mine, was composed of three separate stages: fitting, mining, and sublevel drift liquidation. The following sections of this paper describe only the details of mining proper, which operation consisted in a typical sublevel caving system application, with regularly repeated operations: drilling, explosive charging, and blasting, followed by gravitational release of spoil, spoil delivery, and relocation of the face equipment.

3.4.1 Blasting works

Each time when mining started in the sublevel drift, the so-called start-up blasting works were conducted, using a different procedure than the standard one, applied during regular mining. After completion of the start-up blasting works (i.e. after a full caving in the whole cross-section of the given mining panel), the coal seam was extracted upon borehole drilling, explosive charging and blasting, in accordance with one of the blasting procedures designed for regular coal mining. Fig. 9 presents a sample diagram of blasting borehole distribution.

Blasting boreholes were drilled for mining purposes, using one or two VPS–01 portable stand drilling machines. Usually, the boreholes for mining blasting had the diameter of 45 mm and the length of up to 30 m. Barbaryt 4HM explosive was mainly used in blasting works. That is a nitroglycerine-based material applied in coal deposit blasting, in the presence of methane. Clay was mainly used as wad in blasting works. Detonations were conducted with the use of the Nitrocord 8 pentrite detonation cord, initiated by either Ergodet 0,45AN instant or Ergodet 0,45A25M millisecond electric igniters.

At the beginning, mining blasting was performed with the application of traditional coal rock mass cutting methods, i.e. using up to 20 m long and up to 45 mm dia. blasting boreholes, with manual

explosive charging and was filling. With time, however, also pneumatic explosive charging was applied in parallel, although the latter method required 75 mm dia. blasting boreholes which allowed for shortening the charging process by half. A PVC hose and a pneumatic blaster were used for pneumatic charging. About 1 kg of the explosive material was pumped into a 1 m long and up to 45 mm dia. blasting borehole. However, in case of 75 mm dia. boreholes, the quantity of the explosive material was about 5 kg per 1 m of the borehole. With the progress of extraction, the results of cutting were analysed and experience allowed for selection of a proper blasting procedure. In particular, the distribution of boreholes, their lengths, and diameters, as well as charge sizes were optimised. Both number of boreholes in the fan arrangement and their distribution were changing depending on local conditions of coal seam location (mainly its thickness, tectonics, and coal R_c). On average, 16–19 mining boreholes were drilled for one blasting job. The boreholes were arranged in three fans, with each row of the fans inclined at a different angle, and the boreholes were of various lengths (Fig. 9). Besides, 4 undercutting boreholes were drilled within the drift walls (2 on each side). We should mention here that the borehole length did not reach the full mining panel height, i.e. boreholes were not drilled and blasted directly under the coal seam roof or under the higher panel collapse zone. A coal shelf about 2 m thick was left and that delayed the roof rock collapse process. Although that process caused loss of a certain coal quantity, it reduced the loss in quality. The boreholes were plugged by clay wads packed in paper containers. When coal was still hanging after blasting and spoil release, additional boreholes were blasted. A unit charge (or the quantity of explosive in one borehole) weighed from 5 to 20 kg and its weight depended on the borehole length. During a single face blasting job (with the total charge blasted), from 100 to nearly 300 kg of explosives were fired. The average consumption of the explosives amounted to ca. 0.29 kg per ton of coal spoil.

3.4.2 Coal release and delivery

After blasting and drift face ventilation, the miners released spoil. The process consisted in the transportation of the extracted coal, using a PZ–1000 conveyor whose crossover station was located within the release zone (Fig. 10 and Photo 1). The conveyor supplied the spoil to subsequent chain and belt conveyors, arranged in a series in the sublevel drift and other workings on the way to the shaft. Released coal streaming was controlled by opening and closing of the internal dropping spoil protections of the MSS section (Fig. 6).

The periods of spoil release were diverse and usually continued for about several dozens of minutes. During that process, the face miners properly opened the MSS internal dropping spoil protections (Item 5, Fig. 7) to control feed to the conveyor and prevent jamming of the face zone under MSS. The miners were also responsible for observation of the spoil stream and stopping delivery when oversize coal boulders fell. Such boulders would be cut by pneumatic hammers or crushers mounted on the PZ–1000 conveyor. Occurrence of oversize coal boulders depended on the effectiveness of the blasting procedure applied. In case of poor blasting works, the conveyor had to be often stopped, which caused reduced face yield and output.

What presented essential experience of spoil release in the Kazimierz-Juliusz Coal Mine was the fact of direct collapse of roof rocks behind MSS, which was also associated with the extent of blasting works (see Section 3.4.1 above). The effect was visible in the void created after the release of cut coal. Coal collapse delay also contributed to obtaining very low losses in coal quality. The caving operation was conducted periodically and the spoil often filled in the whole excavation void behind MSS. Usually when that was the case, the continuation of coal extraction and release works were not justified because of quality losses. The losses were mainly caused by a considerable difference between the coal quantity (1.3 Mg/m^3) and the roof rock quantity (2.5 Mg/m^3), transported fast in the released coal stream. In such cases, once a large collapse of roof rocks was observed and rocks were found on the PZ–1000 conveyor, regular operation was stopped at the mining face. Instead of drilling boreholes, the face equipment was relocated by 3–5 m, followed by the replacement of the collected steel stands with wooden ones. Consequently, a small coal pillar was left, separating the face in the new position away from the roof rock collapse site. That operation was followed by regular mining until another full roof rock collapse. The necessity of keeping protection pillars was increasing with the progress of mining in the given mining field. Consequently, the deposit utilisation indicator was gradually reduced with the progress of extraction in the mining field.

3.4.3 Relocation of the mining face equipment

Preparatory works were conducted after spoil release completion and directly before the relocation of the mining face equipment. The works consisted in the disassembly of the drift support elements and collection of intermediate stands supporting the roof bar, located directly in front of MSS. Relocation of the mining face equipment, including MSS and PZ–1000, was conducted with the use of the sliding gear of the PZ–1000 structure (Fig. 11) and the MSS sliding system. First, the stands were used to move apart the anchor feet of the PZ–1000 sliding gear. Next, the sliding system of the section was connected to the anchor foot, using the PZ–1000 sliding system tie rod. After recovery of the section prepared in that way, a controlled movement was performed along the route 2–4 m long. Next, the section was moved apart and another MSS section was relocated as before.

The process continued with the use of separated anchor feet and hydraulic drives of the sliding gear to move the whole conveyor of the section, usually by the MSS relocation distance, i.e. 2–4 m. Once the new equipment location was reached, another mining work cycle started, with borehole fan drilling.

3.4.4 Mining face ventilation

Owing to a high endogenous fire hazard existing in the Kazimierz-Juliusz Coal Mine and the use of explosives in mining operations, mining face ventilation was carried out by the application of a separate sucking duct ventilation system, with a fan mounted within the exhaust air stream on the stepped ramp.

3.4.5 Mining panel liquidation

Once the mining face has reached the mining boundary of the given mining panel, the process of removal and disassembly of the subsequent face equipment elements continued. After the equipment had been transported to the new mining face, the process of mining panel was conducted by mounting an insulation plug on the panel outlet to the drift. The plug was usually made of sand and slag backfill. The distance between the front dams of the plug (or the plug length) was about 10 m. In case of a large extent of the cracking zone around the place designated for the plug, injection works were conducted to seal the rock mass.

3.5 Organisation of work and face manning

To maintain the continuity of coal extraction, a four-shift system was operated. All the shifts were the mining shifts, while the necessary repair works were conducted during any of those shifts as organisation of work and procedures allowed, either with mining work interruption or on holidays. The effective work time at the face was about 6 hours per shift. 3 or 4 miners were employed on each shift at the mining face to carry out production operations. The whole mining panel or sublevel drift required 5–6 workers per shift.

4. Production Results Under The Sublevel Caving System In The Kazimierz-juliusz Coal Mine

In 2003, sublevel-caving mining started in Fields A and B of the south-western part of Section M–3, where coal deposit inclination was about 45° and its thickness reached 16–24 m. The length of mining panels (or sublevel drifts) did not generally exceed 200 m in those mining fields. The mining depth reached 280–550 m. The mining operations were completed in those fields in 2009. Later, until 2015, extraction was continued in subsequent Fields E, G, and C, lying at the depth of 120–340 m, with the coal deposit thickness reaching from 16 to nearly 20 m and the inclination from 40 to even 50°.

The subsequent sections of this paper present the experiences gained mainly during the first period of coal mining in Fields A and B. Owing to the prototype nature of the specific coal mining operations, the operations were subjected to careful monitoring also in respect of the mining influence on workings, surrounding rock mass, and land surface.

4.1 Deposit utilisation indicator and spoil impurities

In the first two or even three mining panels of Fields A and B, the deposit utilisation indicator was determined at the level of more than 0.8. Within the same fields, but three or four panels below, the indicator dropped even below 0.6 and generally remained at that level until the conclusion of mining operations. The average deposit utilisation indicator in Fields A and B was determined at 0.65. However, a

very low coal impurity content (gangue content), not exceeding 3%, was obtained at that fairly low deposit utilisation indicator.

4.2 Output and productivity

The production output during the application of the sublevel caving system was considerably fluctuating. A daily output from one mining face amounted to more 600 Mg on the average, with the peak value exceeding 1,000 Mg per day. The production output depended to a large extent on the coal deposit parameters. Such factors as faults, local deposit thickness reduction, or inclination drop were usually reflected in step changes in output. Assuming the average employment rate at the level of 5 persons per shift per face, the average daily face output amounted to 30 Mg per person.

4.3 Operational costs of the mining face

In the initial period of mining, the costs of the mining face, including the costs of labour, materials, and electricity, reached the level of 10 euros/Mg and the costs were continually dropping. In the third year of mining, the costs reached the level of 6 euros/Mg and that level was maintained until the end of mining operations. Also, the so-called factory costs (i.e. face costs increased by the costs of executing preparatory workings, transportation, deliveries, and ventilation) displayed a similar trend, dropping from more than 30 euros to ca. 18 euros/Mg.

5. Conclusions

The sublevel-caving mining system presented here (patented in Poland in 2004) constitutes a unique face mechanisation solution, designed for coal extraction from thick and steeply inclined coal deposits. Application of that system allowed one mine to extract more than 12 mio. Mg of coal from Seam 510, in the period from 2003 to 2015. Effective face protection solutions and maximum possible work mechanisation caused that no serious accidents were recorded in the mining fields. Despite a low production output level, the Coal Mine obtained a positive financial result each year, owing to high quality of coal extracted from Seam 510 at considerably low operating costs and expenditures for mining face fitting.

Declarations

Ethical standards

The authors declare that the manuscript submitted presents the experiments comply with the current laws of Poland.

Conflict of interest

The authors declare that they have no conflict of interest.

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Figures

Figure 2

Cross-section of Seam 510 in Mine Section M-3

Figure 4

Subdivision of Seam 510 into mining panels, with extraction sequence [4]

Figure 5

Sublevel caving system diagram

Figure 7

Stepped ramp diagram

Figure 9

Rectangular steel support of the sublevel drift 1 – steel roof bar made of two V25 sections, 2 – Valent steel friction stand, 3 – welded steel mesh strut, 4 – double acting steel brace, 5 – timber lining, 6 – steel anchor, with a steel mesh strut.

Figure 11

An MSS section, from the internal and external sides 1 – internal cover of the roof bar, 2 – external cover of the stringer, 3 – external cover of the roof bar, 4 – internal cover of the stringer, 5 – internal protection against dropping spoil, 6 – external protection against dropping spoil

Figure 13

Locations of the MSS and PZ-1000 sections in the mining face

Figure 16

PZ-1000 conveyor, with a sliding station and MSS 1 – MSS set, 2 – PZ-1000 conveyor route, 3 – another chain conveyor, 4 – PZ-1000 drive, 5 – sliding station

Figure 17

Sample distribution of mining blasting works at the mining face

Figure 19

Coal release diagram [4]

Figure 21

Structural diagram of the conveyor with a sliding station 1 – conveyor movement drives, 2 – anchor foot, 3 – tie rod of the sliding system connected to the MSS sections

Figure 23

Photo 1. View of the face when spoil was released [4]