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Stress-state monitoring of coal pillars during room and pillar extraction

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ABSTRACT

Current mining activities of the OKD mines are primarily focused on coal seams within the Karvina Formation in the Karvina sub-basin. A considerable amount of coal reserves are situated in protection pillars that lie under built-up areas. The longwall mining method is not applicable in these areas because significant deformation of the surface is not permitted. For this reason OKD is considering using alternative methods of mining to minimise subsidence. The room and pillar method has been trialed with specific coal pillars in order to minimise strata convergence. The method was implemented in the shaft protective pillar at the CSM Mine and is the first application of the room and pillar mining method within the Upper Silesian Coal Basin. Mining depth reached up to 900 m and is perhaps the deepest room and pillar panel in the world.

To determine pillar stability, vertical stress was measured in two adjacent coal pillars which are diamond in shape and located within a row of pillars forming the panel. Two pillars diamond in shape and slightly irregular sides were approximately 860 m^2 and 1200 m^2 in size and 3.5 m high To measure the increase in vertical stress due to mining, four stress cells were installed in each coal pillar. Four 5-level multipoint rib extensometers measured displacements of all sides within each monitored pillar. The results of stress-state and pillar displacement monitoring allowed pillar loading and yielding characteristics to be described. This data and other analyses are essential to establishing procedures for a safe room and pillar method of mining within the Upper Silesian Coal Basin.

1. Introduction

The Czech part of the Upper Silesian Coal Basin (USCB) region, where OKD mines operate, is densely populated with residential and industrial infrastructure. A considerable amount of coal lies under some of these areas or in protection safety pillars where subsidence is not allowed or has to be minimised. The usual longwall mining methods are not applicable in these areas. For this reason the OKD mines had to consider alternate methods of mining to ensure surface subsidence is kept at acceptable levels. The decision was made to trial the room and pillar method of mining without coal pillar extraction.

The method was trialed within the shaft protective pillar located in CSM-North Mine coal seam No. 30, where the risk of rockbursts was low and roof conditions were acceptable for bolting. However, the variable geology and several faults of regional importance complicated the mining conditions. The mining area was divided into two separate blocks by a significant “Eastern Thrust” fault zone (Grygar & Waclawik, 2011; Waclawik, Ptacek, & Grygar, 2013). Coal thickness varied considerably from 1.8 m to 5.2 m mainly due to the split of the seam. In general, the seam dip ranged from 8° to 17° with the dip occasionally approaching 20°. The mining depth ranged between 700 and 900 m and is perhaps the deepest room and pillar panel in the world.

The room and pillar mining method is usually implemented on the basis of experience gained and practices used elsewhere while taking into consideration different natural conditions and depths. The coal pillar sizes, calculated using accepted empirical methods (e.g. Bieniawski, 1984; Chase, Mark, & Heasley, 2003; Hustrulid, 1976; Mark & Chase, 1997; Salamon, 1970), were uncertain due to

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complex strata geology. As there is no relevant experience of using this method in the Upper Silesian Coal Basin, an extensive monitoring system was implemented to enable the mining trial to continue safely. The monitoring was focused on the load bearing capacity of coal pillars and strata deformation changes induced by the room and pillar mining method. The monitored database used to measure whether the room and pillar method is successful at this depth, provides the necessary information for the verification of this method and its future application in conditions experienced in the USCB.

2. Methods

2.1. Natural conditions in the monitored area

The geological setting in the area of shaft protective pillar CSM-North Mine is quite complex. The targeted coal seam, No. 30, used for the trials, is at a depth of approximately 700 m–900 m below the surface. Above the coal seam there is a 300 m thick complex carboniferous rock mass with an overlying tertiary sedimentary rock strata which is 400 m–600 m thick with approximately a 20 m thick quaternary soil overburden. The strata dip oriented in the north-east direction ranges from 8° to 17°. Occasionally the dip of the coal seam can reach up to 20°.

Within the proposed mining area, the thickness of seam No. 30 is extremely variable. In places the seam splits in to several separate coal seam layers. Interchangeable layers of sandstone, siltstone and coal seams are present. Seam No. 30 separates only in the south-east part of the shaft protective pillar with thickness that varies from 1.8 m to 2.2 m. The seams n.n. (untitled seam), No. 31 and No. 32 merge with seam No. 30 towards the north-west. This substantial and complex coal seam (consisting of seams 30 + n.n. + 31 + 32) has a thickness of up to 5.2 m in the northwest part of the protective pillar area.

In the monitored pillar area (pillars *V1* and *V2* in Fig. 3) and in the panel *V* trial area the 3 m thick seam consists of coal seams 30 and n.n. The monitored pillars are at a depth of approximately 850 m below the surface. The vertical profile around coal seam No. 30 is shown in Fig. 2. The immediate roof above coal seam No. 30 consists of a thin 0.1 m thick sandy claystone layer. This layer is relatively weak and disturbed with slickensides present on the surrounding bedding planes. Above this is 5 m thick siltstone overlain with 6 m thick medium-grained sandstone and 0.3 m thick coal seam No. 624. The roof of seam No. 624 consists of 5 m thick siltstone overlain with a 10 m thick bench of fine-grained sandstone and 4 m thick coal seam No. 29b.sp.l. The vertical distance between seams No. 30 and No. 29b.sp.l is around 26 m.

The immediate floor below mined seam No. 30, located in the pillar monitoring area, consists of 0.5 m thick siltstone underlain by 0.6 m thick coal seam No. 31. The interbedded siltstone and sandstone layers follow down to coal seam No. 32 located some 10 m below the monitored pillars (seam No. 30).

There are several faults of regional importance in the area of the CSM-North shaft protective pillar (see Fig. 1). There is the wide tectonic zone of the Albrechtice Fault with a total throw of up to 420 m located in the west area. The dip of this fault ranges from 60° to 65° towards the West. In the northern area "Fault A" is present with a throw of up to 100 m and a dip of 60° towards the North. "Fault B" in the south part of the area has a throw of around 10 m with a dip ranging from 55° to 70° towards the South.

The significant regional tectonic fault zone "Eastern Thrust" (Grygar & Waclawik, 2011; Waclawik et al., 2013) divides the area of the protective pillar into two separate blocks with different geotechnical conditions. According to existing knowledge, the Eastern Thrust has a very small dip ranging from 10° to 35°. The Eastern Thrust strike is generally in the NE–SW direction with a dip towards the NW. Vertical displacement fluctuates around 5 m, but the range of horizontal displacements is usually much greater and can range from tens to hundreds of meters. Characteristic changes in the Eastern Thrust dip with depth have been observed and may be correlated with the transition to interlayer slips. Experience shows that these thrust fault features have a significant effect on the geotechnical conditions within rock mass.

Inside the protective pillar area, which is surrounded by faults of regional importance, the rock mass is typically disturbed by a system of small so-called seam faults. The uplift on these seam faults is mostly greater than 0.1 m but typically does not exceed 1 m.

2.2. Monitoring equipment

Monitoring of stress and the deformation state of rock mass is an essential requirement for the design of a safe and successful room and pillar method that can be applied in the Czech part of the Upper Silesian Coal Basin. The room and pillar mining method is usually carried out on the basis of experience and practices that have been gained and used under different geological conditions and depths. The geology in the area and the depth of cover indicated that empirical methods of calculating the pillar loads (e.g. Bienawski, 1984; Chase et al., 2003; Hustrulid, 1976; Mark & Chase, 1997; Salamon, 1970) may not be appropriate and could be unreliable. No experience of room and pillar method exists within the USCB area therefore pillar monitoring had to be used to measure the capacity and the deformation characteristics of the coal pillars.

An extensive monitoring system was implemented to measure the load profile across the coal pillar and the deformation characteristics in the pillar during mining. The monitoring was performed in two coal pillars within panel V (location A). The pillars which are diamond in shape and have slightly irregular sides were approximately 860 m^2 and 1200 m^2 in area and 3.5 m high.

In the context of stress and deformation, the following areas were covered:

- Deformability of rock overlaying the room and pillar roadways,
- Measuring pre-mining stress and stress change monitoring in rock and coal during mining,
- Deformability of coal pillars,
- Load on the installed cable bolts,
- Roadway convergence monitoring.

To monitor roof deformation, fourteen pairs of 5-level multipoint extensometers monitored roof displacements (VE1 to VE14 in Fig. 3) and eleven strain gauged rockbolts (VS1 to VS11 in Fig. 3) were installed at various locations. Two 3-dimensional CCBO stress overcoring cells (Nakamura, 1999; Obara & Sugawara, 2003; Stas, Knejzlik & Rambousky, 2004) were used to measure the pre-mining stress in the area (VCCBO1 and VCCBO2 in Fig. 3) and eight 3-dimensional CCBM stress change monitoring cells (Stas, Knejzlik, Palla, Soucek, & Waclawik, 2011; Stas, Soucek & Knejzlik, 2007) were installed to measure stress changes during mining (VCCBM1 to VCCBM8 in Fig. 3). Four 1-dimensional hydraulic stress monitoring cells were installed at various depths in each pillar to measure vertical stress (VSC1 to VSC8 in Fig. 3), four 5-level multipoint rib extensometers measured displacements of all sides within each monitored pillar (VEH1 to VEH8 in Fig. 3), seven hydraulic dynamometer load cells measured the cable bolt loads installed at the roadway intersections (VD1 to VD7 in Fig. 3) and the roof and rib convergence was measured at key locations.

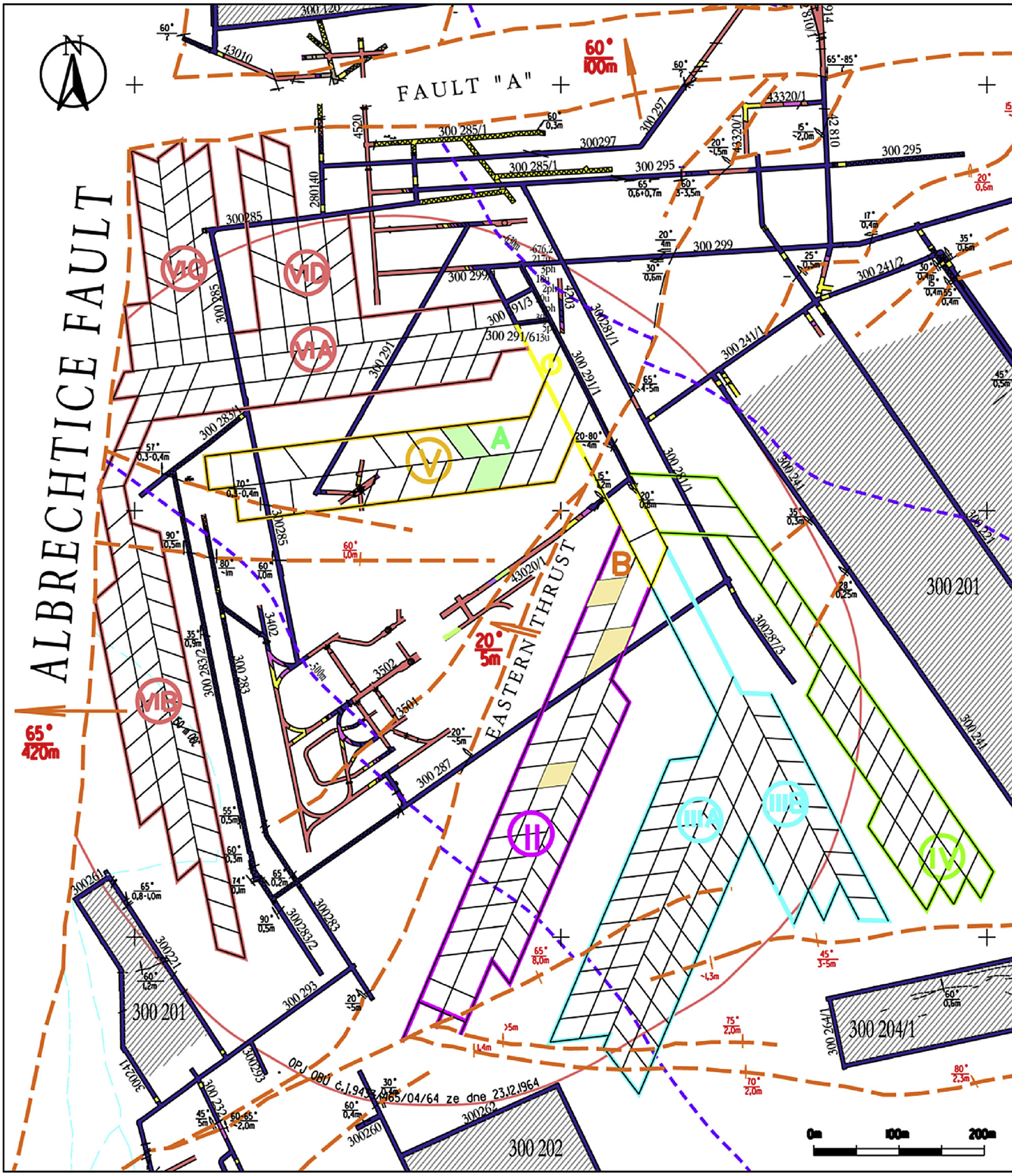

Fig. 1. Tectonic situation and position of monitored pillars in panel *V* (locality A) and panel *II* (locality B).

The instrument locations are shown in Figs. 3 and 4. The coal rib displacements together with the convergence measurements (VP1 to VP9 in Fig. 3), changes in vertical pillar loads and the monthly 3D laser scanning of the overall roadway displacements (roof, rib and floor heave) provided data to evaluate pillar stability. Large seismology and seismo-acoustic monitoring was also undertaken to supplement the data.

2.3. Technical description of coal pillar stress-state monitoring

To determine pillar stability, vertical stress was measured in two adjacent coal pillars located within the row of pillars forming the panel. To measure the increase in vertical stress due to mining, four borehole hydraulic stress cells made by HMA (Australia) were installed in each coal pillar. Two pillars which are diamond in shape

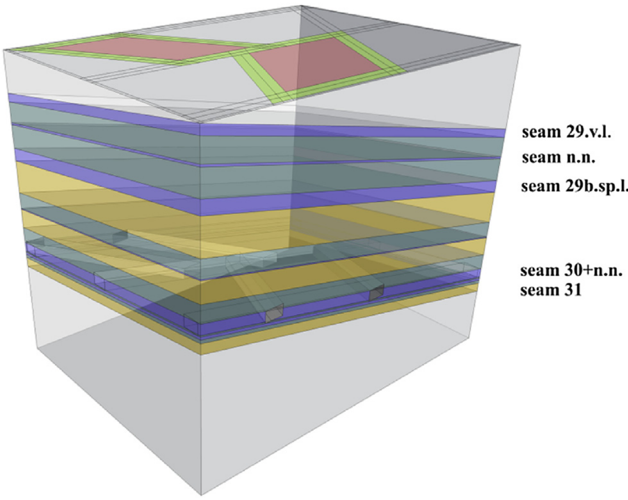

Fig. 2. 3D model of the monitored pillars area in panel V (locality A). Coal seams – blue, siltstones – green, sandstones – yellow.

and have slightly irregular sides were approximately 860 m^2 (*V2*) and 1200 m^2 (*V1*) in area and 3.5 m high. Four stress cells were installed mid height in the 3 m thick coal seam of pillar *V1* and pillar *V2* at depths of 3 m, 6 m, 8 m, 10 m and 4 m, 8 m, 11 m, 15 m respectively (see Table 1). The installation boreholes were designed to suit the seam inclination and heading advance. Position of each stress cell was chosen to measure the extent and formation of the coal pillar fractured zones due to mining. The stress cells were installed after two sides of each pillar were formed.

The initial set pressure in stress cells VSC5, VSC6 and VSC7 (installed in the larger pillar, V1) were set incorrectly to the value of 29 MPa even though the producer of these cells recommended 10 MPa only. These high initial pressures may have permanently fractured the coal around the installed stress cells giving incorrect readings during subsequent mining. Therefore the useful stress monitoring results were limited to the smaller pillar only (V2).

The hydraulic borehole stress cells (HMA) are a soft inclusion type of cell consisting of an inflatable flat jack with 150 mm long platens. The cells were placed in 51 mm diameter boreholes and

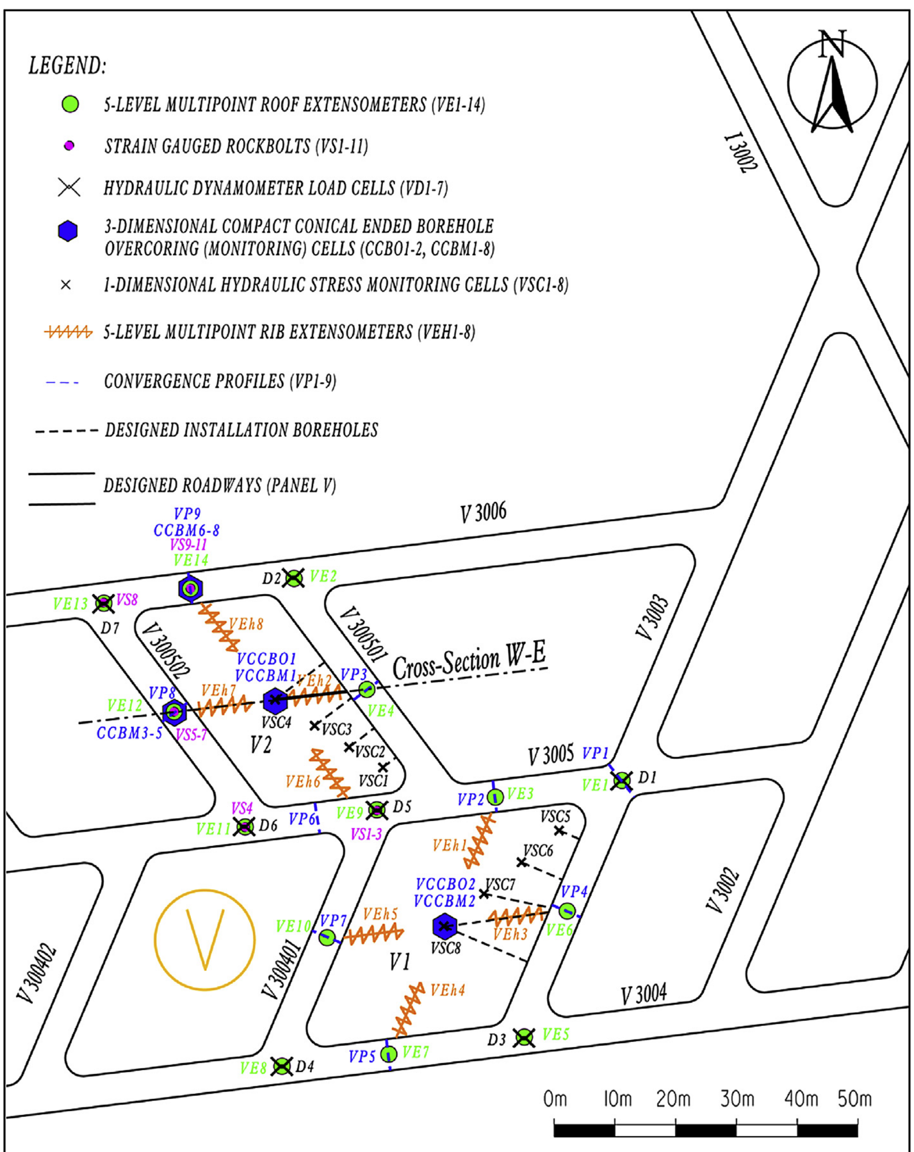

Fig. 3. Project of stress-deformation monitoring in panel *V* and position of monitored equipment within monitored panels *V1* and *V2*.

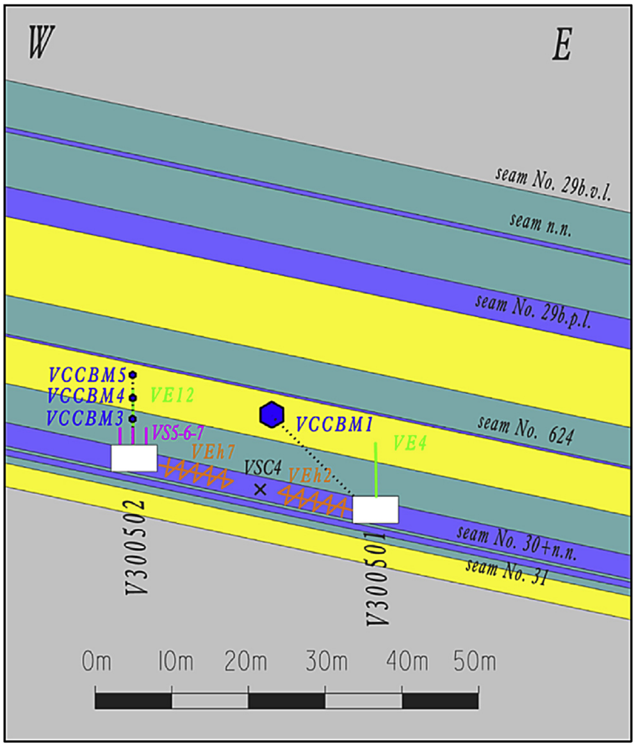

Fig. 4. Cross-section across monitored pillar *V2*. Coal seams – blue, siltstones – green, sandstones – yellow. See to Fig. 3 for legend of monitored equipment.

then pressurized. Each stress cell was monitored using a 60 MPa pressure gauge. Each stress cell unit was 250 mm long and 51 mm in diameter. The pressure range of these cells was 0–60 MPa.

The stress cells' HMAs were installed in accordance with the procedure stated below:

- borehole drilling with a diameter of 60 mm using a pineapple drill bit,
- lengthening the borehole by 1 m using a drill bit with a diameter of 51 mm,
- the cleaning of the borehole by water,
- oriented installation of the stress cell by rods,
- the setting of initial stress by a hydraulic jack.

3. Results and discussion

3.1. Measured stress changes in coal pillars

The installation of stress cells in the *V2* pillar started after the North roadway *V3006* and the East roadway *V300501* were driven. The stress change monitoring in the smaller pillar *V2* started after stress cells *VSC1, VSC2, VSC3* were installed on the 26th January and stress cell *VSC4* was installed on the 30th January (see Table 1).

At the initial stage of monitoring, stress in the smaller pillar *V2* started to increase after the third, south side (*V3005*) of the pillar was partly driven. When the development of roadway *V300401* began, the load of stress cells *VSC2* and *VSC3* increased by 12 MPa and 6 MPa respectively (see Fig. 5). In contrast, the load of stress cell *VSC1* decreased below the initial pressure indicating that the coal around the cell had yielded.

The load of stress cells *VSC2* and *VSC 3* gradually increased to 18 MPa and 12 MPa respectively after the larger coal pillar *V1* was formed (see Fig. 6). The load of stress cell *VSC4* located in the centre of the coal pillar increased to 3 MPa only. The load of stress cell *VSC1* (3 m depth) stabilised at 0 MPa.

After the smaller pillar *V2* was formed, the load of stress cell *VSC4* abruptly increased to 26 MPa (see Fig. 7) while the load of stress cells *VSC2* and *VSC3* stabilised at 15 and 10 MPa respectively, indicating that the pillar sides continued to yield towards the centre. The load of cell *VSC1* at a depth of 3 m recorded no changes and oscillated around 0 MPa indicating that the yielded zone around the cell did not increase in load any further.

The load measured by stress cell *VSC4* continued to increase up to 40 MPa while the next southern pillar was formed (see Fig. 8) indicating that the pillar intact core size continued to decrease towards the pillar centre and the load on the central part of the pillar was still increasing. The vertical load of other stress cells *VSC1, VSC2* and *VSC3* was already stabile at values of 0 MPa, 15 MPa and 12 MPa respectively.

When mining continued away from the *V2* pillar towards the West, the load of stress cell *VSC4* increased to its maximal value of 49 MPa (date 26/3/2015). Shortly after that, the load of this cell sharply decreased to 37 MPa while at the same time the load on stress cell *VSC2* fell abruptly to 0 MPa. Because the area was still active as indicated by small seismic events, it is possible that the sub-vertical fractures propagated through the massive roof at the vicinity of the monitored pillars and suddenly overloaded the pillar core. This may explain the brief overload of cell *VSC4* followed by the sudden drop in pressure measured by both stress cells *VSC2* and *VSC4*. The load measured by stress cell *VSC4* continued to decrease over a period of almost 1 month to about 21 MPa, then it decreased abruptly to 0 MPa on the 21st April (see Fig. 9). Cell *VSC3* still oscillated at around 10 MPa for the majority of the time until the mining advanced two pillars away in the west direction when on 31st of May abrupt unloading of the cell occurred. It is assumed that, due to the stress concentration around the cell, coal yielded which in turn unloaded the stress cell. While the abrupt unloading of stress cells *VSC2* (depth 6 m) and *VSC3* (depth 8 m) can be explained by the continuous yielding of the pillar sides towards the centre, the unloading of stress cell *VSC4* was probably caused by high stress concentrations and subsequent coal failure around the

Table 1
Stress cell installation data.

Stress cell no.	Monitored pillar no.	Roadway no.	Chainage[a] [m]	Installed depth [m]	Initial pressure [MPa]	Date of installation
VSC1	*V2*	*V300501*	8.0	3	10	26/1/2015
VSC2	*V2*	*V300501*	14.0	6	10	26/1/2015
VSC3	*V2*	*V300501*	20.0	8	10	28/1/2015
VSC4	*V2*	*V300501*	28.0	10	10	30/1/2015
VSC5	*V1*	*V3003*	104.0	4	29	8/1/2015
VSC6	*V1*	*V3003*	110.0	8	29	8/1/2015
VSC7	*V1*	*V3003*	116.0	11	29	8/1/2015
VSC8	*V1*	*V3003*	126.0	15	10	12/1/2015

[a] Note: Chainage is distance from the beginning of the mine roadway.

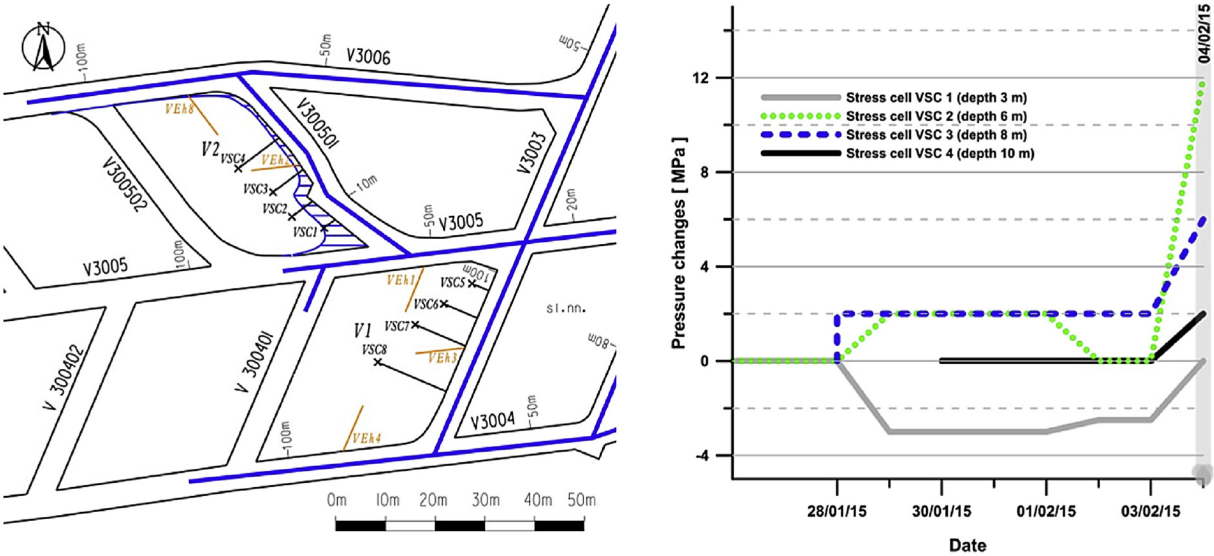

Fig. 5. Stage 1 (blue) showing mining progress and development of the yield zone and initial V2 pillar load results (up to 4/2/2015).

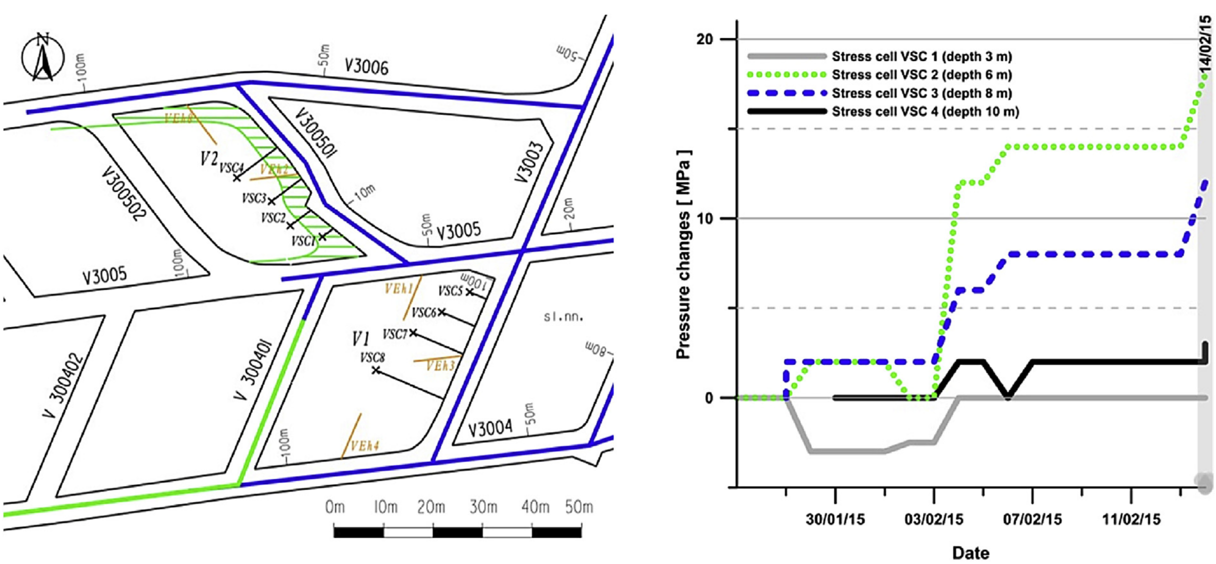

Fig. 6. Stage 2 (green) showing mining progress and development of the yield zone and V2 pillar load results when the formation of pillar V1 was completed (up to 14/2/2015)

installation hole unloading the stress cell in the otherwise highly stressed area at the pillar central core.

3.2. Stress and its influence on the coal pillar

Gradual vertical stress increase measured across the *V2* coal pillar indicated the development of the yield zone within the pillar perimeter which gradually reduced the size of the pillar core. The abrupt unloading of stress cells *VSC2*, *VSC3* and *VSC4* indicated that coal around the hydraulic stress cells has yielded and subsequently coal failure occurred. Several pillar extensometers that measured coal deformation clearly indicate the boundary of the yielding zone, confirming this trend. The development of deformation zones within coal pillar *V2* can be described by five basic stages of mining.

During the first stage of mining, two pillar sides (mined roadways *V3006*, *V300501*) were formed and the third south side (roadway *V3005*) of the pillar was partially driven (up to 4/2/2015) as shown in Fig. 5. At this stage all of four hydraulic pillar stress cells (*VSC1* to *VSC4*) were already installed including the horizontal extensometers *VEH2* and *VEH8*. The extensometers showed that the coal ribs were fractured to a depth of at least 1 m (*VEH 2*), however no early rib movement was observed at the extensometer (*VEH8*). The hydraulic stress cell *VSC1* located at a shallow depth of 3 m did not show any increase in stress, indicating that the cell was located within the severely yielded rib side. From this we can conclude that, at that stage, the boundary of yielded coal at the narrow South-East corner of the pillar was deeper than 3 m (see Fig. 5).

During the second stage of mining (up to 14/2/2015), when pillar *V1* located to the south of the monitored pillar *V2* was fully formed, the vertical load on the three stress cells *VSC2*, *VSC3* and *VSC4* increased gradually (see Fig. 6). From the pillar horizontal extensometers we can conclude that the coal pillar yield zone occurred at a depth of up to 5 m from the rib side. The gradual

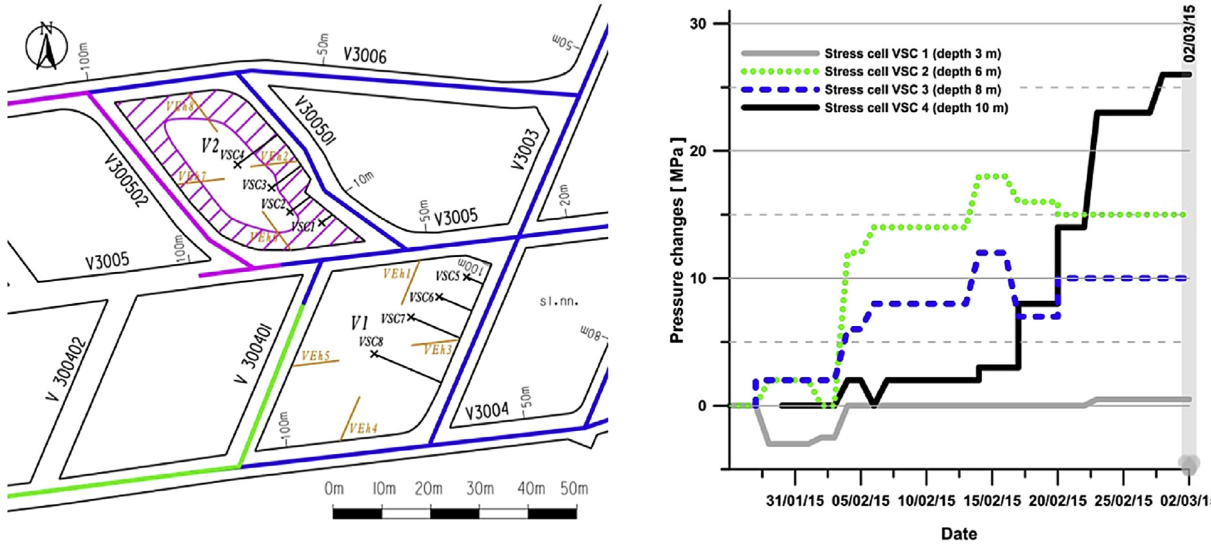

Fig. 7. Stage 3 (violet) showing mining progress and development of yield zone and V2 pillar load results when the formation of pillar V2 was completed (up to 2/3/2015)

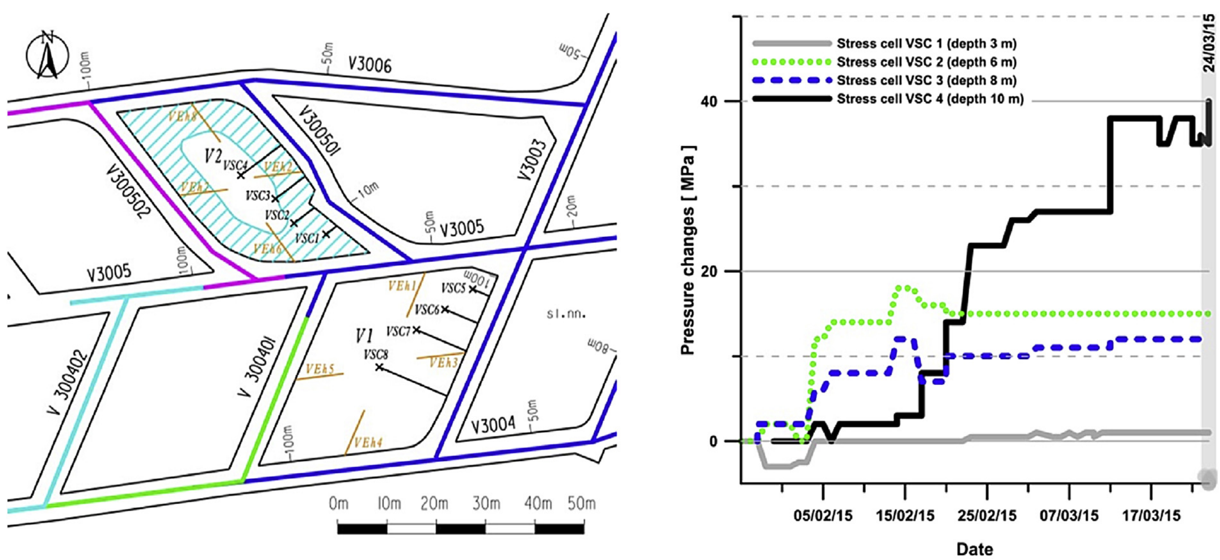

Fig. 8. Stage 4 (cyan) showing mining progress and development of yield zone and V2 pillar load results when the next southern pillar was formed (up to 24/3/2015)

increase in vertical load measured by the three stress cells VSC2, VSC3 and VSC4 indicated that the pillar sides continued to yield further towards the centre (see Fig. 6).

During the third stage when pillar *V2* was fully formed (up to 2/3/2015), hydraulic stress cell *VSC4* located at a depth of 10 m in the pillar increased to 26 MPa while cells *VSC2* located at a depth of 6 m and *VSC3* at a depth of 8 m stabilised at 15 MPa and 10 MPa respectively indicating that the pillar sides continued to yield towards the centre. The horizontal extensometers *VEH7* and *VEH6* that were already installed at this stage, indicated the depth of the yielded zone to be 5 m while *VEH2* and *VEH8* measured a yield zone of up to 7 m in depth from the rib side (see Fig. 7).

During the fourth stage, when the pillar to the west of pillar *V1* and south of the monitored pillar *V2* was formed, the load of stress cell *VSC4* increased to 40 MPa (see Fig. 8). The vertical load of all other stress cells *VSC1, VSC2* and *VSC3* was already stable at values around 0 MPa, 15 MPa and 12 MPa. From the data all horizontal extensometers located within pillar *V2* (*VEH2, 6, 7, 8*) indicated that the pillar yield zone extended up to 7 m from the rib side towards the pillar core.

During the fifth stage of mining, when mining continued towards the West, the load of stress cell *VSC4* increased to the maximum value of 49 MPa (date 26/3/2015) but shortly after that, the load sharply decreased to approximately 27 MPa. At the same time abrupt unloading of stress cell *VSC2* to 0 MPa occurred. Within less than a month stress cell VSC4 gradually unloaded to approximately 21 MPa and then abruptly unloaded to 0 MPa (see Fig. 9). The vertical load measured by *VSC3* fluctuated slightly around 10 MPa and abruptly unloaded on 1st June 2015. Further assessment of the intact core size was not possible because the relevant extensometry and the stress cells near the central part of the pillar ceased to work. However the speed of deformation monitored by the horizontal extensometry and the convergence measurements indicated a rapid slowdown at the later stage of monitoring. This implies that the pillar deformation and its capacity may have been stabilizing.

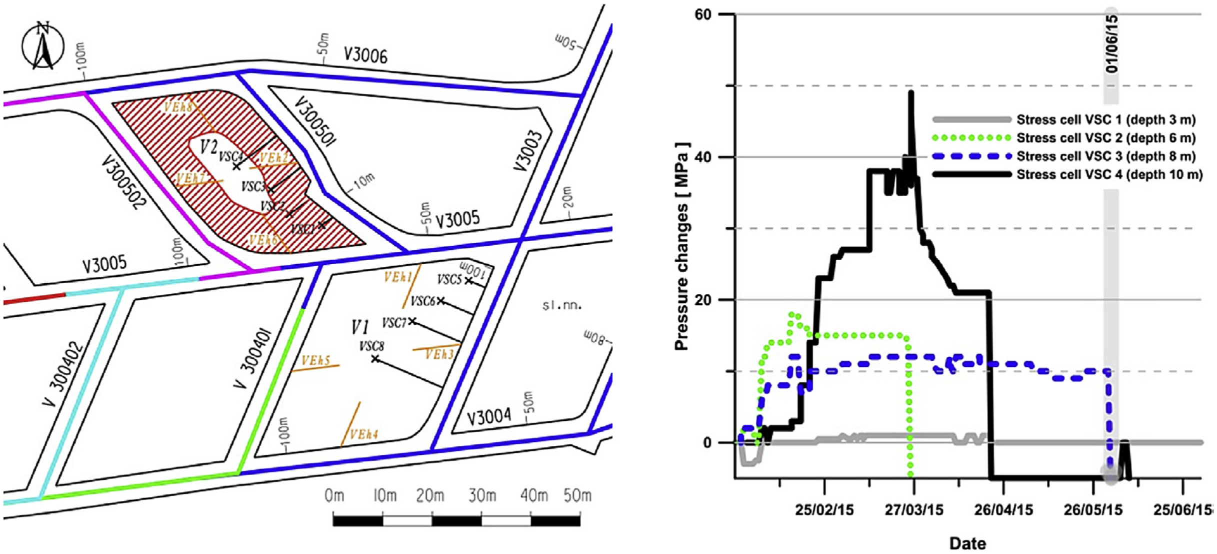

Fig. 9. Stage 5 (red) showing mining progress and development of yield zone and V2 pillar load results after mining two pillars away West of the monitored site (up to 1/6/2015).

4. Conclusion

The room and pillar method has been trialed in the shaft protective pillar at the CSM Mine within the Upper Silesian Coal Basin. Coal pillar monitoring was essential as this was the first application of the room and pillar mining method in USCB mines at great depth. Two coal pillars located in seam No. 30 were intensively monitored to ensure the stability of the panel and safe mining procedures.

Due to the incorrect installation of the cell within the larger coal pillar (*V1*), the results were limited to the smaller pillar (*V2*) only. The results of stress-state and pillar displacement monitoring allowed the pillar loading and yielding characteristics to be described. The data showed that the monitored coal pillar sides displaced substantially into the roadway mainly due to a large vertical stress field and the presence of weak slickensides above and below the seam. This mechanism has caused large floor heave, rib convergence and relieved some of the confining stresses that usually build up within a pillar, therefore weakening the coal and causing the pillar to yield. The instruments indicated that a small pillar core remained relatively intact and provided support to the mined area. Mining of panel *V* has already finished, however monitoring will continue to investigate long term pillar stability and the influence of the next room and pillar panel *II* to be trialled in the near future.

The current data from panel *V*, rock strength tests, numerical modelling and observations will form the basis for the room and pillar design of panel *II*. The experience gained from this monitoring has also been used to design the instrumentation for panel *II*. Three pillars approximately 590 m^2, 690 m^2 and 1070 m^2 in size will be monitored as shown in Fig. 1 (location B). It is expected that more accurate analysis will be available from the next, more comprehensive instrumented site where more pillars of various sizes will be monitored. These measurements, numerical modelling and other analyses are essential in order to establish procedures for the safe room and pillar method of mining within the USCB.

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