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Rock mass dynamics during coal longwall mining at great depth

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Abstract
The process of deep mining of mineral deposits dynamically affects the overlying part of the rock mass and the ground surface, both during the mining phase and after mine closure. Understanding of the detailed dynamics has been made possible in recent years by the application of new techniques for continuous measurement of changes in surface deformation. Two years ago, we designed and initiated a unique high-precision Automatic Geodetic Monitoring (AGM) system in the CSM mine area (Upper Silesian Coal Basin, Czech Republic). The monitoring system comprises two automatic total stations with an integrated 3D laser scanner, GNSS sensors and other ancillary equipment, situated in the roofs of skip towers of the mine. Since the CSM mine is still in operation, sufficient data is currently available to evaluate the dynamic formation of the subsidence trough as a result of mining at great depth. The millimetre accuracy of the interpreted AGM data allows to capture in detail the process of the propagation of mining effects to the surface. The monitoring is conducted on an hourly basis, providing a markedly different dataset on the actual ground surface subsidence during mining than was previously possible with the use of levelling, which was typically carried out several times per year. The paper presents a detailed evaluation of ground surface subsidence during the mining of a 2.5 to 2.75 m thick coal seam at a depth of 1140 to 1250 m below the surface. The measured data of subsidence at selected points are evaluated and correlated with the mining advance, geomechanical and mining conditions, and registered induced seismicity. The interesting development of the subsidence trough as a function of the mining advance and geomechanical conditions, as well as the estimation of the parameters for the theoretical calculation of surface displacements are presented in the paper.

Keywords
Rock mass dynamics, vertical displacements, undermining effects, induced seismicity

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1 Introduction

Surface movements, i.e. subsidence and horizontal displacement, as well as the resulting surface deformations, such as tilting, curvature, and horizontal longitudinal deformation above the deeply exploited deposit, occur in conjunction with the extraction of the mined mineral. This process gives rise to the formation of free underground spaces, which are subsequently filled with the overlying rocks.

Immediately following the extraction of the mined mineral, there is a rearrangement and change of stress fields in both the overburden and the underlying rocks of the newly created free spaces (in the case of a mine in the Ostrava-Karvina Coalfield area of the mined seam). Once the strength limit of the overlying rocks is exceeded, they undergo a shift (or filling) towards the centre of gravity of the mined seam space. It is evident that in instances of extensive mining, such as longwall mining, this phenomenon will also manifest with a certain time delay on the surface above the mined coal seam.

In the event that the overburden is susceptible to accumulating stress (due to its geological composition comprising thick layers of solid supporting rocks), the enlargement of extracted seam spaces will result in the sudden failure (cracking) of these overburden supporting rocks, accompanied by energy emission and the emergence of induced seismicity.

Subsequently, the movement of the overburden rocks, including the overlying Carboniferous formations, towards the centre of gravity of the extracted spaces is transmitted to the surface of the deposit, where it is manifested by the formation and development of a subsidence trough. This can then be measured by geodetic methods.

It is evident that the initial manifestation of induced seismicity will occur in the overburden supporting rocks, manifesting as localised seismic phenomena.

The correlation or correspondence between spatiotemporal data on the course of mining of the longwalls, induced seismicity and information about the subsidence trough on the surface can be determined if such data are available.

2 Description of the mine and the surface situation

2.1 Mining

The area of interest contains a multiseam hard coal deposit, which is part of the Czech part of the Upper Silesian Coal Basin. The coal seams are exploited by the CSM mine in Stonava town, where deep excavation is carried out using longwall mining techniques. Figure 1 illustrates the location of the CSM mine within the broader topographic context for basic orientation.

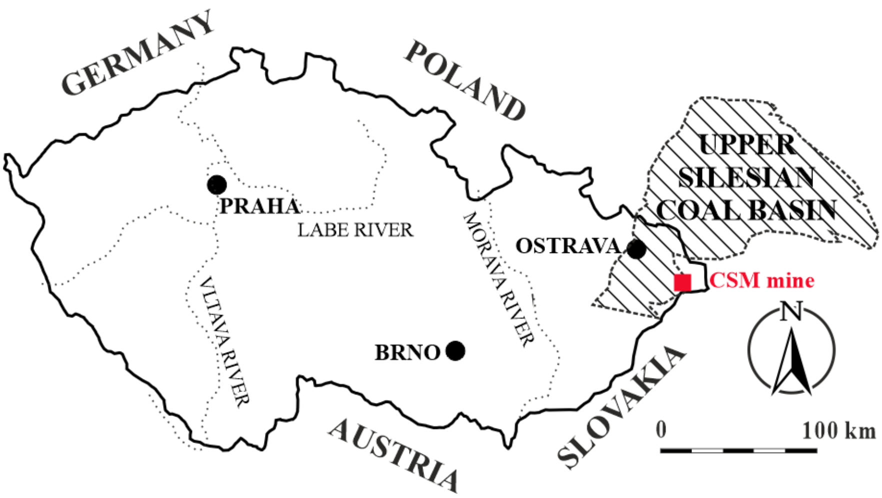

Fig. 1 Location of the CSM mine in the Czech Republic

The article assesses the mining operations conducted in three distinct seams: seam 29b, seam 40, and the Natan seam. These mining activities were carried out within the effective distance of points P01 – P05 (see Fig. 4), which are monitored on a permanent basis by the Automatic Geodetic Monitoring (AGM) system. The mean mining depth was 695 m in seam 29b, 995 m in seam 40 and 1176 m in the Natan seam. The effective distances in these seams were determined using the limiting angles of influence (Carboniferous 65°; cover 55°) and the thicknesses of the overlying layers of the Carboniferous formation and the overlying formation. The effective distance in seam 29b was determined to be 436 m, 574 m in seam 40 and 657 m in the Natan seam. In the area of interest, seam 29 was mined to a thickness of 2.1–3.5 m, seam 40 to a thickness of 3.1–4.65 m and the Natan seam to a thickness of 2.5–2.75 m.

2.2 Surface subsidence

The AGM system was designed to obtain measured surface movement data of sufficient frequency and quality for the assessment of surface deformations in connection with deep mining. In this paper, data from five points (P01 – P05) that have been stabilised on the land pipeline construction and which are equipped with reflecting prisms are used. These points have been measured within the AGM.

2.2.1 Geodetically measured surface subsidence

The height measurement of surface points is conducted automatically at hourly intervals. These are trigonometric measurements obtained using an automatic Leica Nova MS60 MultiStation total station in conjunction with a Leica GMX910 GNSS receiver, with the measured values transmitted online in real-time. A detailed description of the hardware components and service software used, as well as the overall methodological approach to the functioning of the entire AGM system, is thoroughly described by Kajzar et al. (2023).

The evolution of the subsidence of individual points is illustrated in Figure 2. Due to the method of stabilisation of points on the supporting elements of the pipeline, the relief of the landscape and the method of use of agricultural areas, there was a temporary loss of monitored data in the period from August 2023 to October 2023. This was caused by shading of the reflecting prisms by vegetation. Subsequently, damage was also incurred to points P01 and P02. Monitoring of these points was reinstated in November 2023.

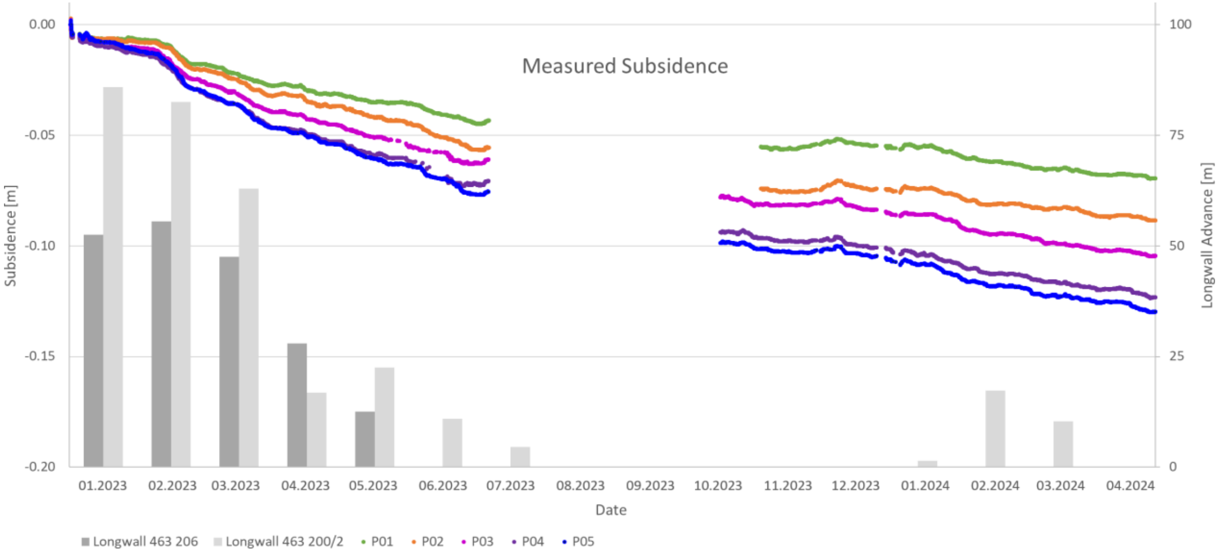

Fig. 2 Measured subsidence of points P01 – P05

2.2.2 Theoretically calculated surface subsidence

The theoretical subsidence of the monitored points P01 – P05 (see Fig. 3) was calculated using the Knothe method (Knothe, 1984), which is a well-established and commonly used approach in this field. It is important to note that the theoretical calculation represents the impact of mining on the surface in an idealised environment and does not account for the actual conditions of the given location from a structural-geological or geomechanical perspective. The estimation of the parameters of the mining effects for the theoretical calculation of the vertical surface displacements was based on a retrospective analysis of the monitored data and previous experience.

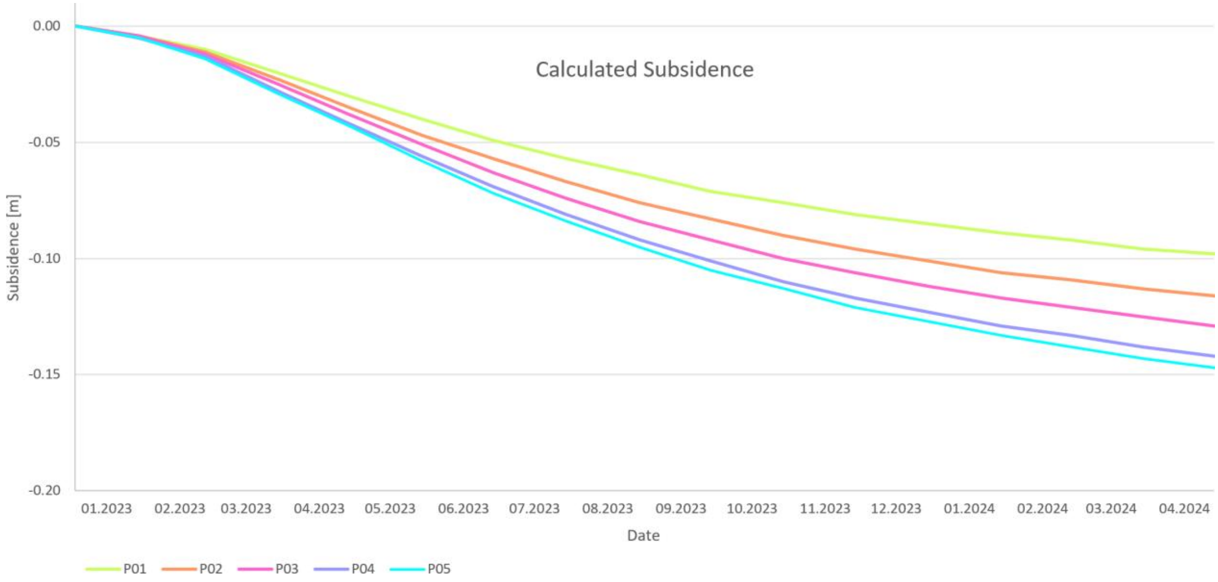

Fig. 3 Dynamic calculation of subsidence of points P01 – P05

In order to analyse the monitored subsidence, a dynamic calculation of the effects of undermining on the surface was performed using the Schenk time function (Schenk 1997), the parameters of which are as follows: the total duration of surface movements T = 40 months and the delay of the first signs of mining on the surface Re, which was set to zero in consideration of the ongoing longwalls 463 200/2 and 463 206. In the case of the assessment of surface subsidence related to the initial measurement of surface points' heights prior to the commencement of mining activities, this parameter of the time function is selected to be non-zero, with a duration of between one and three months. The mining coefficient value of 0.7 was selected based on the measured surface subsidence increments and long-term experience with the theoretical determination of surface subsidence in the specified region (Jiránková 2014).

The subsidence trough model was determined through a static calculation of the effects of undermining on the surface. The theoretical calculation encompassed all the longwalls within the effective area of the observed surface points that were mined over a five-year period preceding the commencement of surface monitoring, in addition to all longwalls that were mined during the aforementioned monitoring period (see Fig. 4). The mining coefficient of all these longwalls was thus determined to be 0.7. In consideration of the potential for surface subsidence to reactivate during the evaluated period, the longwalls mined in seam 29 prior to five years before the commencement of monitoring were also incorporated into the subsidence trough model. The theoretical calculation included the longwalls of seam 29 with a mining coefficient of 0.1. The ground subsidence trough model is illustrated in Fig. 4 through the use of isocatabases, which are isolines representing equal ground surface subsidence.

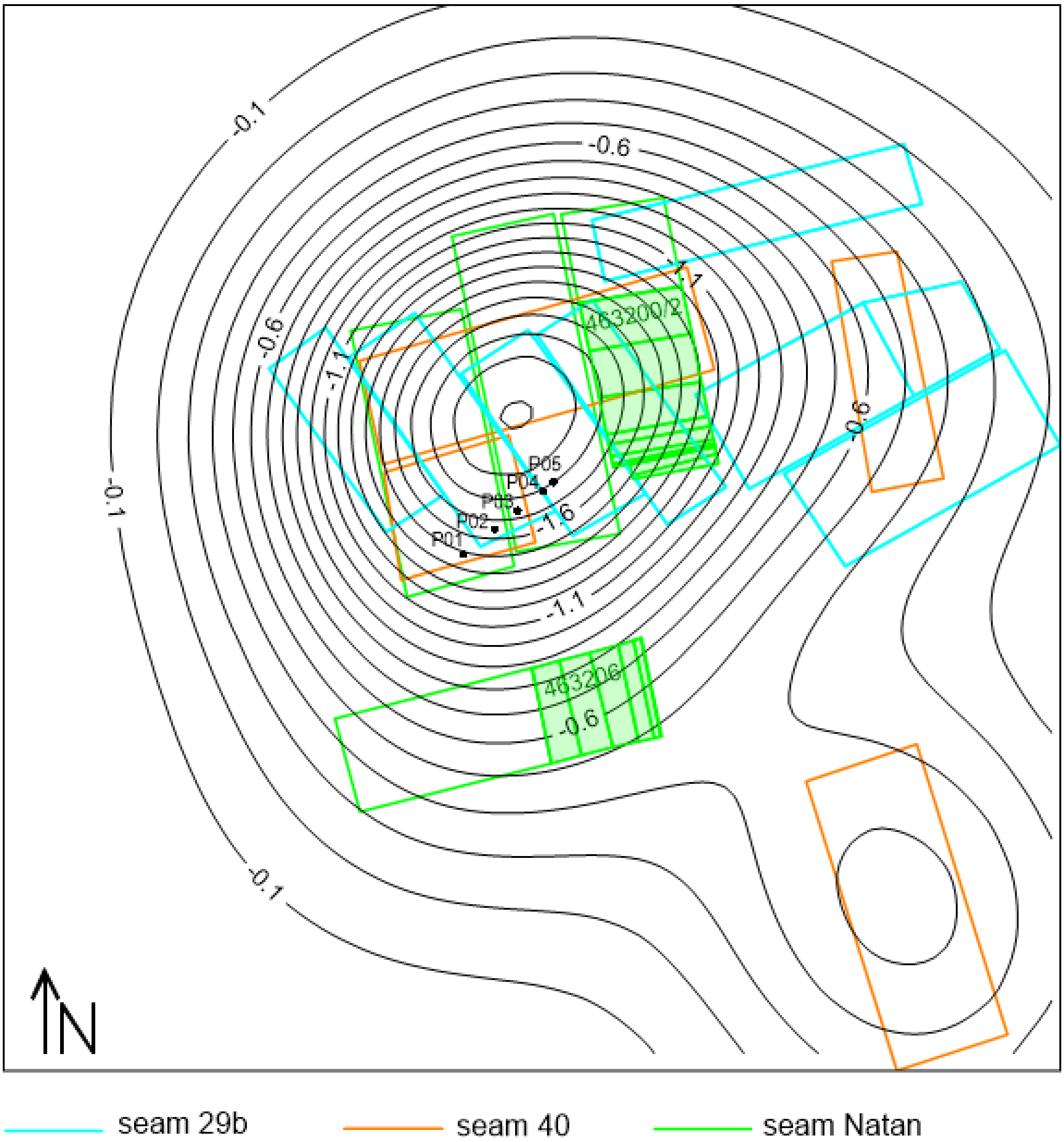

Fig. 4 Ground subsidence trough model (in metres)

2.3 Induced Seismicity

As a consequence of alterations in stress-strain fields within the overburden of individual longwalls due to their mining (enlargement of excavated areas) and particularly if the higher overburden is susceptible to stress accumulation due to its geological composition (the presence of thick layers of solid accompanying rocks), which is also the case at the presented site, means that enlarging the excavated seam spaces after exceeding the strength limit of these immediate overburden rocks will result in brittle failure, accompanied by energy emission and the occurrence of induced seismicity.

In order to prevent rockbursts, continuous seismological monitoring is conducted, comprising both a local network of stations at individual mines and a regional network of stations surrounding the Karviná subbasin. The Regional Seismic Monitoring Network is comprised of 10 tri-axial short-period WDS seismometers (f_0 = 2.0 Hz), of which six are situated in boreholes (depth 30 m), three are installed underground in active mines, and one is located in a short gallery at the Ostrava-Krásné Pole seismic station. The frequency range of the network is 2–32 Hz, with a recorded seismic signal dynamic of approximately 120 dB at a sampling frequency of 125 Hz. Secondly, data from the local seismological network of CSM mine were also employed. The stations that comprise this network are situated in the local mine and are equipped with mono-axial, low-frequency, and low-periodical vertical SM-3 seismometers. The fundamental specifications of these seismometers are as follows: input sensitivity 16 µV–5 mV, maximum amplification 74 dB, frequency range 1.5–20 Hz, and sampling frequency 100 Hz (Konicek and Schreiber 2018).

Figure 5 shows the mining situation with the distribution of individual longwalls (the mined seams are distinguished by colour) with registered seismicity. During the mining of longwalls 463 200/2 and 463 206 (see Fig. 6), mainly weak seismological events (up to the order of 10^2 J) were registered. For the simplification, only registered seismological events with energies of 10^3 J and higher are shown in Figure 5. In the case of longwall 463 200/2, mainly seismic events of the order of 10^3 J were registered in the longwall area itself, especially in the phase of developing the longwall face from the initial crosscut and in the phase of advancing the longwall face to the termination line, and occasionally stronger seismological events of the order of 10^4 and 10^5J outside the longwall contour, especially towards the east. A larger number of seismological events of the order of 10^3 and 10^4 J were registered NE of the longwall contour in the area of the edges of the mined seam 40 in the overburden. In the case of longwall 463 206, a larger number of seismological events of the order of 10^3 – 10^5 J were registered in the longwall area and towards east, which is related to the area not mined in all the mentioned seams (seams 29b, 40 and Natan).

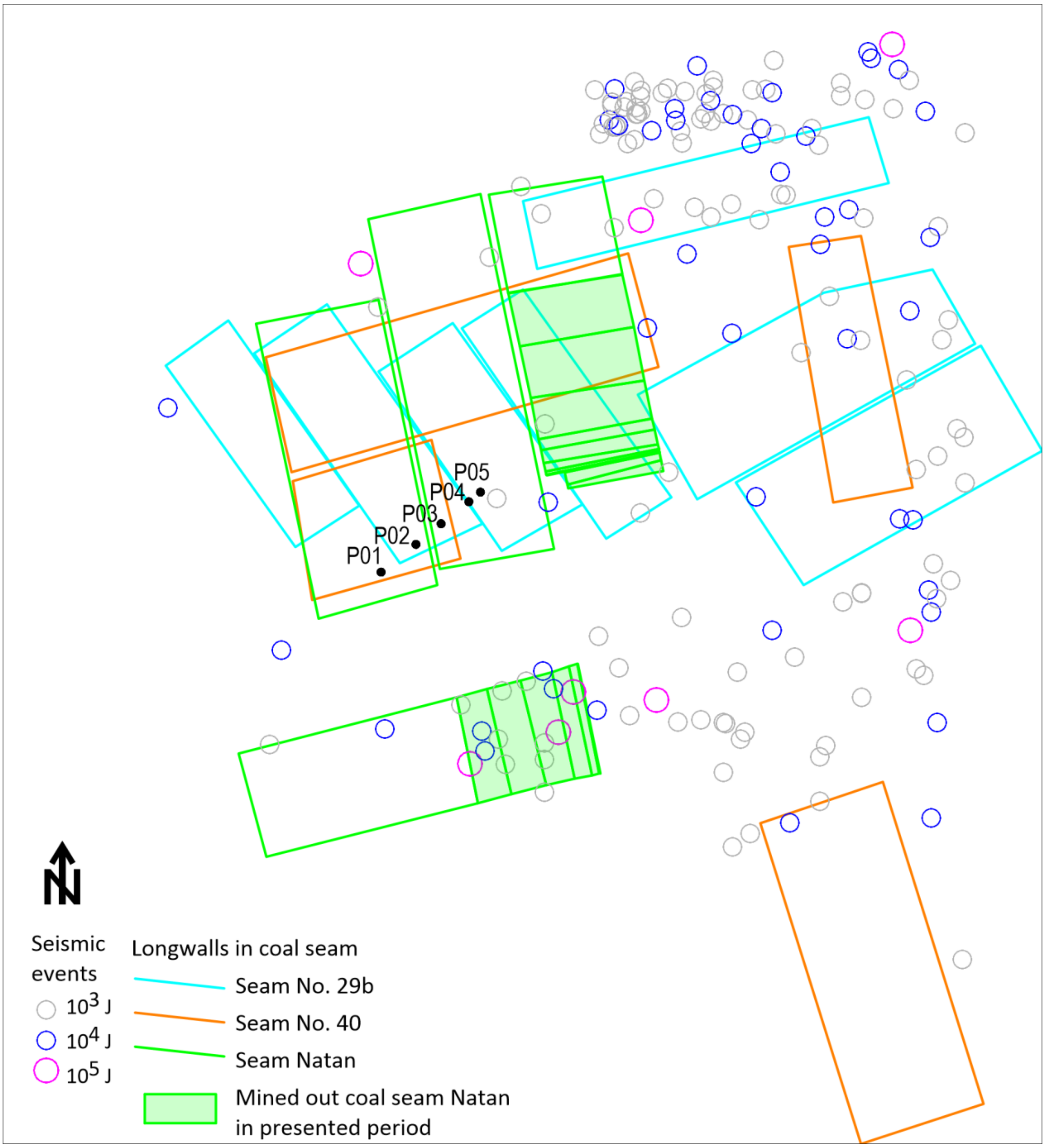

Fig. 5 Registered induced seismicity during mining of longwalls in Natan coal seam in period from January 2023 to April 2024

3 Results

The analysis of surface subsidence in connection with the mining of longwalls 463 200/2 and 463 206 in the Natan seam is based on the following data: interpreted heights of surface points measured within the AGM, dynamic subsidence determined by the Knothe method, registered seismic events and mining intensity. The findings are presented through the interpretation of measurement values for point P05 (see Fig. 6), which is situated in the closest proximity to the location of the most significant subsidence (see Fig. 4). The period from the commencement of monitoring of surface points P01 – P05, from January 2023 to April 2024, was subjected to evaluation.

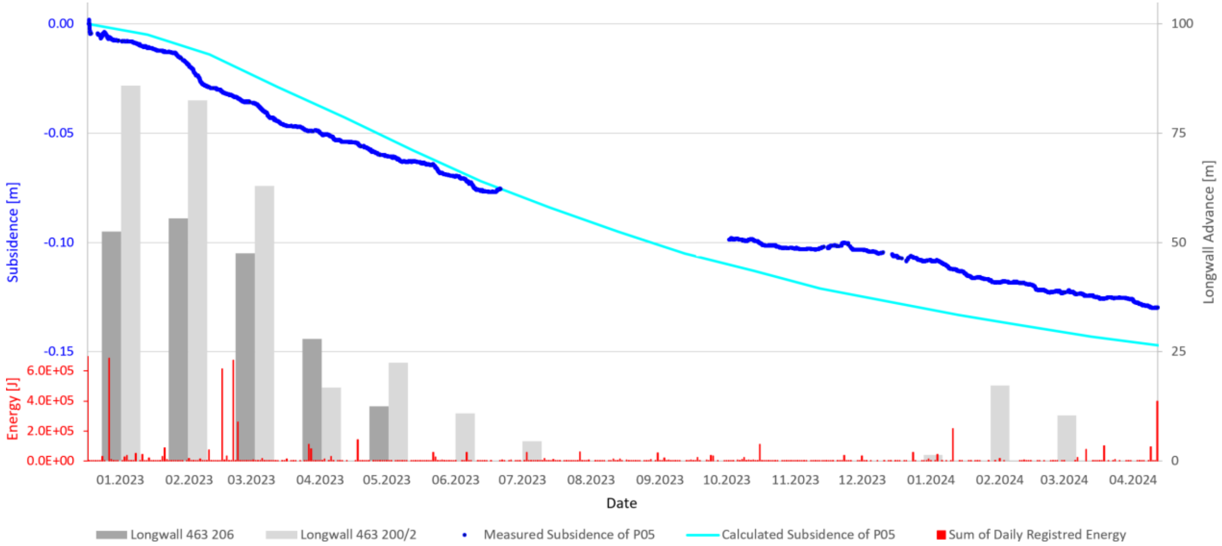

Fig. 6 Combined graph of interpreted subsidence of point P05 measured by AGM, dynamic subsidence of point P05 determined by the Knothe method, monthly advance of longwall faces 463 200/2 and 463 206 and registered seismic events related to induced seismicity

The monitored points were stabilised on the surface at the time when approximately one-third of the longwall 463 200/2 (i.e. 155 m out of the total longwall length of 444 m) had been reached. Approximately two-thirds of the longwall 463 206 (i.e. 349 m out of the total longwall length of 543 m) were mined out, as illustrated in Figure 4. With the completion of both longwalls, the monthly advance was reduced for technological reasons from the average regular monthly advance of 80 m to 8 m in the case of the longwall 463 200/2 (whose mining was interrupted in the period from August 2023 to January 2024) and from the average regular monthly advance of 50 m to 12 m in the case of longwall 463 206 (see Fig. 6).

The occurrence of induced seismicity in the study area is related to the intensity of mining, which results in the fracturing of the rock mass. During the period of mining with the usual monthly procedures of 80 and 50 m respectively, four significant seismic events with an energy of 2.6–6.9×10^5 J were recorded. The subsequent period of resumption of mining on the 463 200/2 longwall was accompanied by two events, the first with an energy of 2.2×10^5 J at the beginning of the resumption of mining and the second with an energy of 4.0×10^5 J approximately one month after the end of mining. Throughout the assessed period, seismic events with an energy of up to 10^5 J were recorded, which are characteristic of the regular disturbance of the rock mass in the area under consideration.

4 Conclusions

The results of the monitoring of surface points provided information on the vertical movements of the surface located on the slope of the formed subsidence trough, as illustrated in Figure 4. The monitored subsidence was subjected to a dynamic calculation of the impact of mining on the ground surface. In consideration of the ongoing mining of the evaluated longwalls, as previously mentioned, the zero value of the delay of mining effects on the surface was selected. During the period of mining with a normal monthly advance of the longwall face (from January to July 2023), the movements and deformations were observed to spread evenly through the overburden to the surface. It can be observed that the monitored subsidence is slightly overestimated, with the differences ranging from 0 to 15 mm. During the period between August and October 2023, the data was not available for monitoring.

Following the resumption of monitoring in October 2023, the diminishing impact of mining on the ground surface became evident. The monitored subsidence is slightly underestimated, with differences ranging from 12 to 23 mm. Given the limited extent of mining on longwall 463 200/2 between January and March 2024 and the considerable depth of mining (approximately 1200 m), the impact of this mining was insignificant and contributed minimally to the observed increase in ground surface subsidence during the decay phase.

The findings suggest that while surface subsidence remains an significant factor in mining operations, the overall impact can be mitigated through thorough planning and comprehensive monitoring. The study further highlights the necessity of continuous geodetic and seismological surveillance to assess long-term subsidence trends and potential occurrence of seismic activity associated with underground mining operations.

Acknowledgement

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