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Seismic activity and flooding of hard coal mines in the Ostrava-Karvina Coalfield

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Abstract

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Keywords

flooding of mines, post-mining seismicity, coal mines, water level, ground surface movement

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Seismic Activity and Flooding of Hard Coal Mines in the Ostrava-Karvina Coalfield

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Abstract

The termination of mining activities often results in post-mining problems and risks. One of these issues is the flooding of mines. Long-term mining in the Ostrava and Petrvald sub-basins in the Upper Silesian Coal Basin finished in 1994. Tens of coal seams were mined here, and the depth of mining reached more than 1000 m below the surface. Flooding of the Ostrava sub-basin started in 1994. The Ostrava and Petrvald sub-basins were flooded from one half only to prevent water from flooding into the Karvina sub-basin, where mining continued. The continual pumping of water has been carried out ever since. Only low-energy seismic events (up to 10^3 J) were recorded during the periods of flooding and water pumping. Only one high-energy seismic event was recorded here (10^8 J, magnitude of 3.5, 12 December 2017). This study presents the natural and mining conditions regarding the process of mine flooding; and the induced seismicity registered during the flooding of mines and the preservation of water at the stated level. Analysis of the flooding of mines in connection to the registered seismicity is presented. Probable reasons for the low seismic activity during the flooding of mines are also discussed.

Keywords: flooding of mines, post-mining seismicity, coal mines, water level, ground surface movement

1. Introduction

At present, the underground mining of hard coal is coming to an end not only in the Czech Republic but also in many other parts of the world. After closing a mine, the empty spaces gradually become flooded with water. The process of water flooding takes several decades. Experience in the flooding of closed mines shows that ground surface uplifts occur during the filling of underground spaces, in addition to the induction of strong seismicity [1–6]. Some areas in the Upper Silesian Coal Basin (USCB) are missing the overlay of Carboniferous units and Carboniferous rock mass exude on the surface (areas where mining was started). The intensive excavation occurred here in the mid-19th century and culminated in the 20th century. The flooding began after the closure of the

mines in this area in 1994. Many European localities have shown that during the flooding of closed mines, ground surface uplifts of the order of 10 mm/year can occur [7]. However, immediately after the closure of a mine, there is a fading period of the surface subsidence during which the values of the subsidence gradually decrease. During this period, up to 15% of the total surface subsidence occurs. Therefore, surface displacement due to flooding during the fading period cannot be determined. By 2001, the water level had risen to a level over which the water could enter other mines still operating in the Karvina region of the USCB. Therefore, water pumping was started in 2001 to maintain underground water at a safe level. This study discusses the manifestations of registered seismicity and height changes in the surfaces of closed mines during flooding in the Ostrava and Petrvald sub-basins.

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2. Description of area

The Ostrava-Karvina Coalfield is the largest deep mining complex in the Czech Republic and is part of the USCB. The northern area of the basin can be divided according to natural conditions into three main sub-basins, namely, the Ostrava, Petřvald and Karvina sub-basins. The vertical profile of rock mass can be characterised (from the surface) by Quaternary sediments (sands, gravels and soils) or anthropogenic backfill (waste rocks from the Carboniferous rock mass) with a thickness of 10–30 m and approx. 250 m of Baden clays over the Carboniferous units and rock mass.

The USCB is located on the border between the Czech Republic and Poland. The area of this bituminous coal basin exceeds 7–000 km² and is one of the largest coal basins in Europe [8]. Only 1–550 km² of the bituminous coal basin lies in the territory of the Czech Republic, with the remaining area lying in Polish territory [8]. Recently, the extent of coal-bearing sediments in the USCB has been influenced by post-sedimentary erosion. The original extent of the basin was larger [9].

Mining methods were originally implemented from ore mining. The first mining method was coal mining by corridors driving (in many modifications) in coal seams. Parallel corridors were driven in coal seams for a certain distance. The pillars left in the coal seam were not mined. Later, the parallel corridors were connected with cross cuts due to ventilation reasons and to increase the volume of coal mined. The room and pillar method, in many modifications, was used from the 1880s. The room and pillar method with pillar depillaring and control caving or backfilling was mainly used. This method prevailed in the first third of the 20th century. Longwall mining prevailed as a mining method from the 1940s. Longwall mining was adopted here with control caving, as well as with backfilling. Backfilling was used only in areas where subsidence could be decreased (only up to 10% of cases). A special case of mining was steeply inclined coal seams (areas of West saddles, near the Michalkovice and Orlova structures, as shown in Fig. 1). Modifications of the room and pillar method have also been used, and the modification of longwall mining in specific conditions after that.

2.1. Ostrava and Petřvald sub-basin geology

The seams of the Ostrava Formation were mined in the Ostrava and Petřvald sub-basins. The Ostrava Formation is represented by paralic, coal-bearing molasse. The maximum thickness of the Ostrava

Formation reaches 3–000 m and decreases toward the east and south to 100 m or less. From a lithologic point of view, the formations have a heterogeneous character and contain a mixture of sandstones, conglomerates, siltstones, claystones, volcanoclastic rocks and coal beds. Predominantly, there are fine-to-medium grained sandstones (40–60%), with lower concentrations of coarse-grained sandstones and conglomerates. In the Ostrava Formation, there are approx. 170 coal seams with an average thickness of 73 cm. Different sedimentary rocks reflect cyclic repetitions and changes in the environment of deposition in the coastal basin.

The Ostrava Formation is divided into four members, namely, the Petrkovice bends, Hrusovske bends, Jaklovecke bends, and Poruba bends (see Fig. 1). Each of these is several hundred metres thick, and their coal-bearing parts are separated by thick sedimentary sequences with a lack of coal beds. Their deposition was during marine transgressions [9].

The USCB belongs to the most tectonically complicated Paleozoic molasse basins of the European Variscides. This basin has a polytype and conspicuous zonal tectonic pattern. The structural-tectonic development and present-day tectonic situation in the USCB are defined by the overall deformation development of the Variscan accretionary wedge of the Moravo-Silesian area in the apical zone [10]. Several significant factors have influenced the development of the structural characteristics of the basin, including the tectonic style, deformation regime, intensity and kinematics of deformation. The Brunovistulicum formed the basement of the basin in the foreland of Variscan orogeny. The next tectonic development of the USCB was given by the position in the foreland of the Alpine deformation phases of the Western Carpathians.

The USCB includes parts with complicated fold and fold-fault structures (the west Variscan fore-deep), like sections with dominant subhorizontal bedding (Upper Silesian block). A typical west-east cross section in the Czech part of the USCB is presented in Fig. 1.

2.2. Hydrogeological situation

The hydrogeological conditions in the Czech part of the USCB are heavily influenced by anthropogenic activities. The impacts of workings and exploitation, including the deep hydraulic depression induced by the drying of the rock complex, have changed the natural geohydrodynamic systems. Originally separated groundwater bodies have been interconnected.

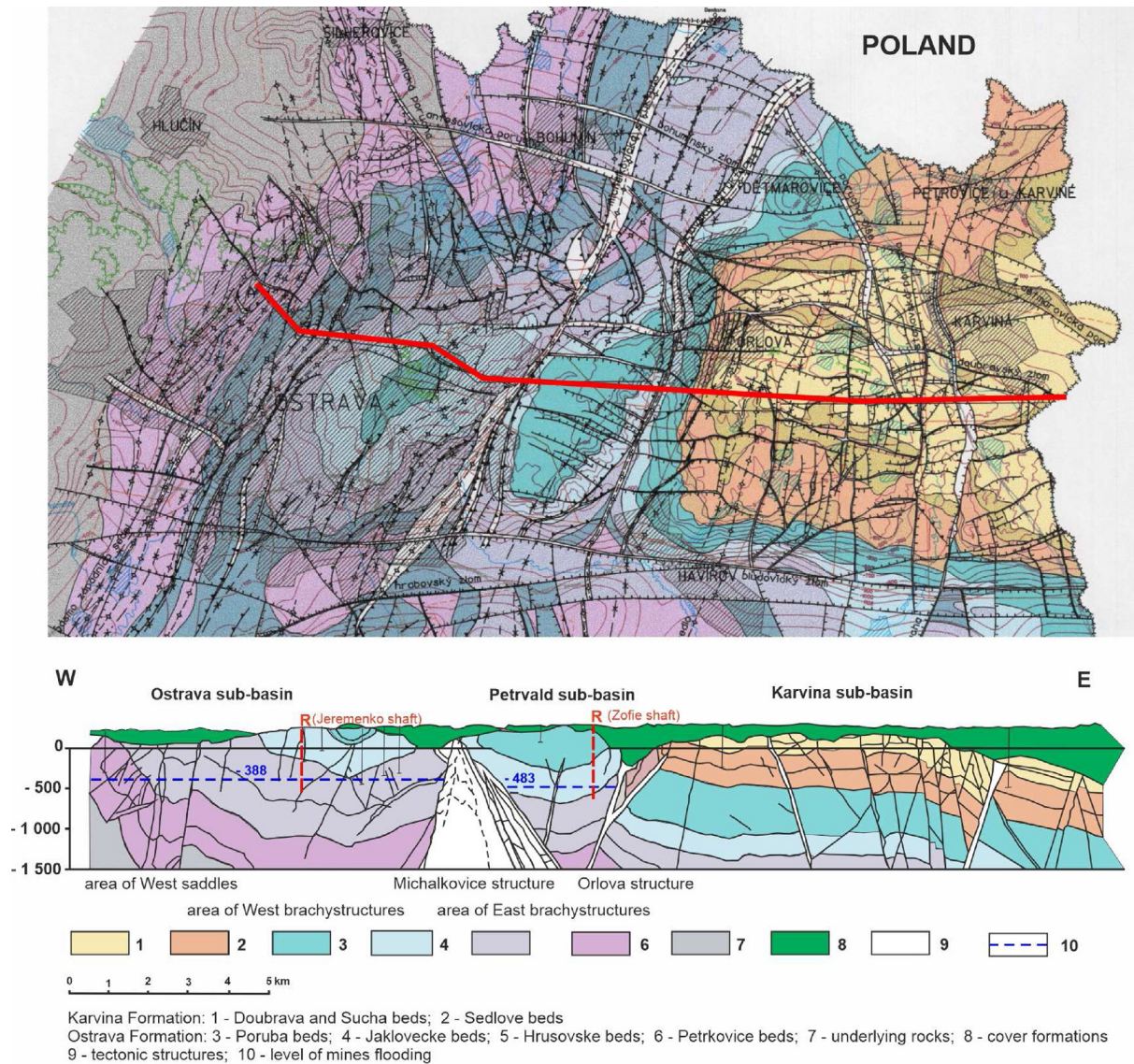


Fig. 1. Simplified geological situation of Ostrava, Petřvald and Karvina sub-basins – geological map above (not in scale; read line – location of cross-section) and cross-section below; modified according to Dopita [9].

In the region outside of the extent of the Beskydy nappes, primarily fissure aquifers of the Upper Carboniferous, porous aquifers of the Early Badenian cover and also in porous aquifers of Quaternary sediments are hydraulically interconnected. In the area of the Beskydy nappes, there are groundwater bodies in the Lower Cretaceous and Paleogene rocks of the nappes of the Western Carpathians that are also hydraulically interconnected.

The following can be ranked among the fundamental natural resources of mine waters which aquifers are characterised in the text by basic hydraulic parameters and which areal and vertical delineations are given by:

- waters of Quaternary groundwater bodies
- waters of groundwater bodies of the Early Badenian cover of the Carboniferous, including basal clastics of the Early Badenian (a so-called detritus horizon)
- mainly the waters of fissure systems of the rock mantle of the Carboniferous
- primarily waters of the fissure and fault systems of the Upper Carboniferous and the deeper underlying rocks of the productive basin sediments.

The initial water inflow into the mines when they were active was summarised in [11–13], without

Table 1. Water inflow into the mines in the Ostrava sub-basin in the period of mining ($l \cdot s^{-1}$) [13].

Mine	Mine pond	Water inflow	Carboniferous	Detritus	Miocene cover units	Quaternary
Odra (1)	Odra	59.7	–	22.0	1.2	36.5
Sverma,	Odra	77.0	–	43.4	3.6	30.0
Hermanice (2)	Ostrava	64.5	–	15.5	15.5	33.5
Ostrava (3)	Ostrava	122.1	4.9	40.0	3.5	73.7
TOTAL		323.3	4.9	120.9	23.8	173.7

Mine claims: (1) Privoz, Koblov; (2) Hermanice, Michalkovice; (3) Hlubina, Jeremenko, Bezruc, Zarubek.

Table 2. Water inflow into the mines in the Petřvald sub-basin in the period of mining ($l \cdot s^{-1}$) [13].

Mine	Water inflow	Detritus, undifferentiated Miocene cover units	Quaternary
Pokrok	38.6	26.7	11.9
Zofie	34.4	21.5	12.9
TOTAL	73.0	48.2	24.8

taking into account for operation the water in the Ostrava sub-basin (Table 1) and in the Petřvald sub-basin (Table 2).

The data presented in Table 1 show that more water was drained by ventilation and transported coal (according to some authors, up to 15%). The water inflow is underestimated in Table 1, and the

real amount was probably higher (approx. $375 l s^{-1}$). This amount was utilised in the amount of $240–260 l s^{-1}$ [11] mainly due to 2.5 higher time of flooding.

The conceptions of “ponds” recommended by Younger [14] were used for the evaluation of post-mining flooding of mines and the definition of hydraulic connectivity on the borders of ponds. The Ostrava sub-basin was divided into two separated “ponds”, namely, the Odra and Ostrava ponds, while the Petřvald sub-basin was defined as a separate pond (see Fig. 2). Hydraulic connectivity was defined between borders of ponds according to the knowledge of the connection of mines through corridors, mined areas of coal seams, tectonic faults and similar.

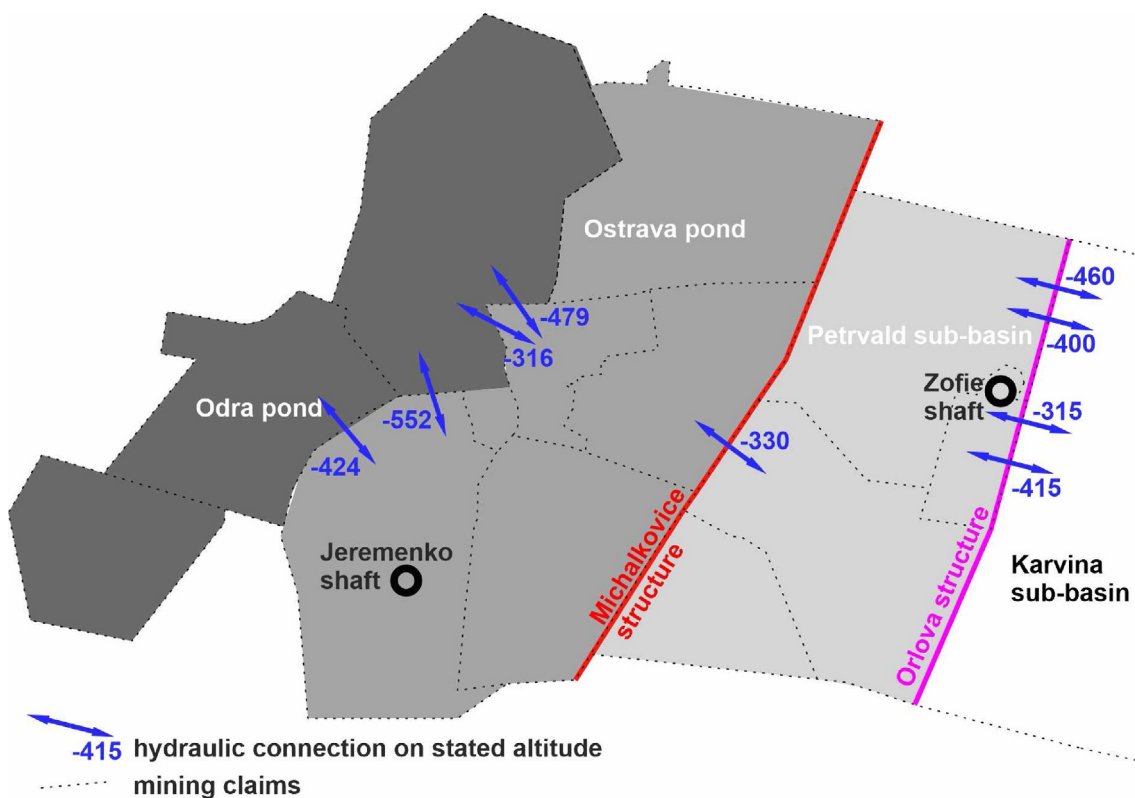


Fig. 2. Definition of separate ponds in Ostrava sub-basin, modified according to Malucha [13].

3. Seismic network and monitoring protocol during operation

There was no seismic monitoring in the Ostrava and Petrvald sub-basins during the mining period, despite rockbursts occurring during mining in these sub-basins. The first mention of a rockburst in the Karvina sub-basin was in the Hoheneger pit in 1912 [15]. There were 106 rockbursts recorded during the period of mining (from 1900) in the Ostrava Formation. The milestone in solving rockbursts in the Ostrava-Karvina coalfield was a rockburst in the Hugo seam at the Trojice mine in Ostrava on 3 September 1936, when four miners were killed and others injured. More details can be found in the Ptacek monograph [15].

Rockburst problems are closely connected with mining in the area of the Karvina sub-basin, where natural conditions are different from those in the Ostrava and Petrvald sub-basins. This is mainly due to the high occurrence of rigid competent rocks (sandstones and conglomerates represent 60–90% of the seam interbed) between coal seams and the thickness of the coal seams is higher (from 3 to 10 m). The decisive impetus for the creation of the

current rockburst prevention system was a rockburst that occurred while mining the residual pillar in seam No. 32b in the sixth block at the Doubrava mine (Karvina sub-basin) on 24 April 1974, which had fatal consequences [15]. Geophysical services gradually became an integral part of geotechnical services from 1977, with the DPB Company commencing the building of the OKR seismological network by establishing a surface station at the 1 May mine. From 1979 to 1981, the seismic station in the Ostrava-Krasne Pole was commissioned (now administered by the VSB-Technical University of Ostrava), and since 1994, it has been included in the Czech Regional Seismic Network. On the initiative of the Institute of Geonics of the CAS, after a powerful rockburst in the ČSA mine, the Green Gas DPB investigated the construction, and since 1992, it has been the operator of a regional net, Seismic Polygon. This seismological system is focused on induced seismicity monitoring in the area of the Karvina sub-basin. Seismological monitoring was placed in the area of the Karvina sub-basin due to the high rockburst risk in the 1980s as a part of the rockburst prevention system.

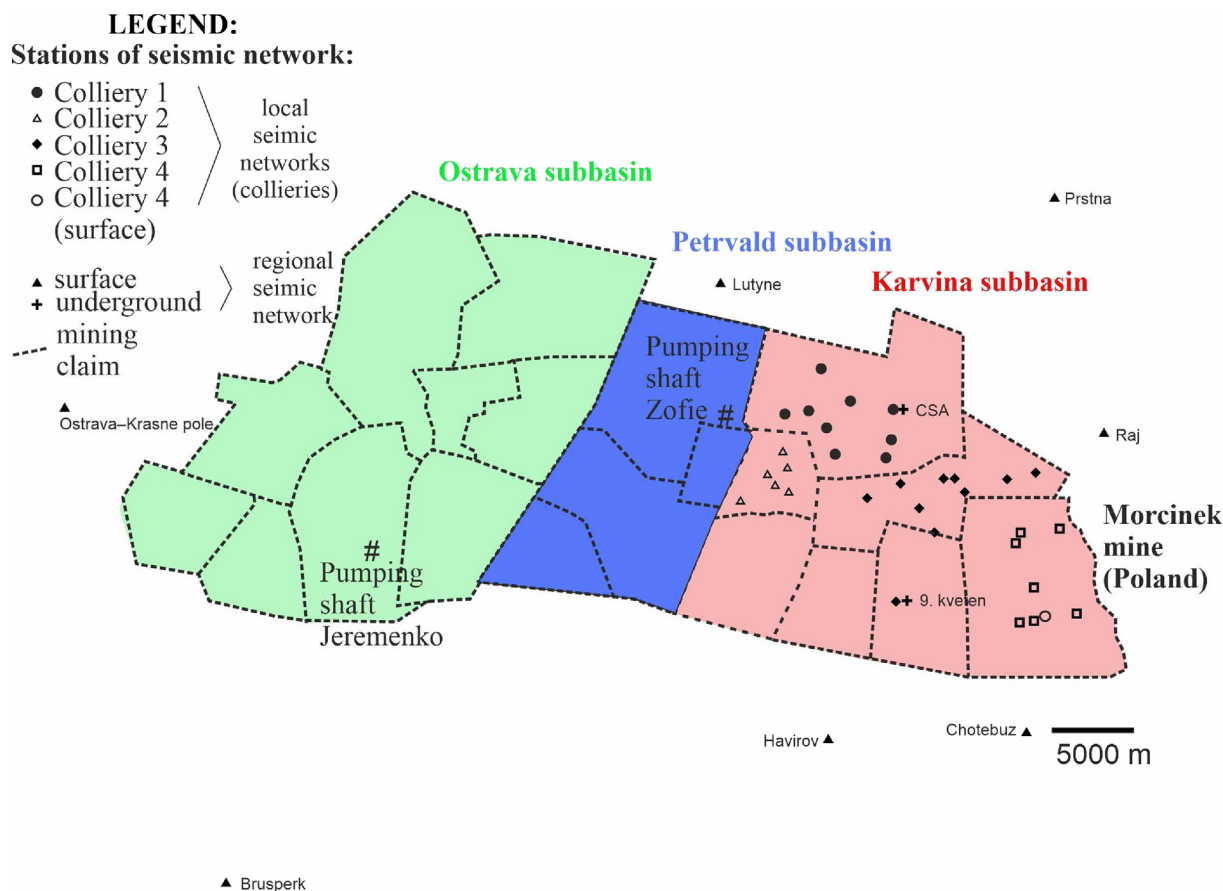


Fig. 3. Mining seismic networks in the Czech part of the USC B (situation in 2015).

The detection ability of this monitoring system overlaps with the area of the Karvina sub-basin. The seismological monitoring system is composed of two seismic networks, namely, a regional seismic network and a local seismic network, on every colliery of the Karvina sub-basin (see Fig. 3), with their data evaluated together. The regional seismic network consists of ten triaxial short-period WDS seismometers ($f = 2.0$ Hz). Six of them are located in boreholes (at a depth of 30 m), three are installed underground in active mines, and one is situated in a short gallery at the Ostrava-Krasne Pole seismic station. The frequency range (f) of the network ranges from 2 to 32 Hz. The dynamics of the recorded seismic signals are ~ 120 dB, with a sampling frequency of 125 Hz [16]. Local seismic networks in every active colliery are equipped with uniaxial, low-frequency and low-periodical vertical SM-3 seismometers. The basic parameters of these seismometers are an input sensitivity of $16 \mu\text{V}$ to 5 mV, a maximum amplification of 74 dB, a frequency range of 1.5–20.0 Hz and a sampling frequency of 100 Hz. The current state of the seismic monitoring networks is depicted in Fig. 3.

Created seismological system in the Karvina sub-basin (see Fig. 3) allows the monitoring of the induced seismicity in the Ostrava and Petrvald sub-basins but with lower sensitivity.

The seismological monitoring established in the Karvina sub-basin started in 1992. Due to this reason, only seismic events in the period of the mining finishing were recorded here, and also in the period of mine flooding and water pumping. Because of this, rockbursts and other related incidents during mining were not recorded in the Ostrava and Petrvald sub-basins.

4. Liquidation of closed shafts

After closing the mines, the main mining works that emerged to the surface were liquidated. In the area of the Ostrava and Petrvald sub-basins, it was the liquidation of the 89 shafts, with the deepest ones reaching depths of over 1000 m. The mine liquidation was carried out with several methods. The first of them was the backfilling of the entire shaft profile with consolidated (cement fly ash and concrete), unconsolidated material (fly ash) or their combination (e.g., at the backfilling of the entire shaft profile with unconsolidated material, while in the intersection area of the shaft and the level gangways (main crosscuts), consolidated material was used). The second method of mine liquidation was to form a concrete plug at the Carboniferous rock mass level. Subsequently, part of the shaft from

the deck to the concrete plug could be backfilled with either consolidated or unconsolidated material. For example, one of the deepest shafts, the Privoz shaft in the Ostrava sub-basin, was excavated to a depth of 1041 m with a circular profile of 7 m in 1942. Its backfilling and final safety were carried out in 1998. At the seventh level, a double-sided concrete plug was made. Above this level, the level gangways were closed by double-sided brick dikes. Below this level, the level gangways were not closed. On the surface, the shaft was closed with a reinforced concrete deck with a closable filling opening and a pipe to control and remove harmful gases. During backfilling, the quality of the backfill material, the amount of deposited backfill material and its properties were checked.

5. Rising water level management protocol

Mining finished, and flooding started in the Ostrava sub-basin in 1994. Since 2001, a preserving water level of altitude -388.5 m below sea level (~ 600 m below the surface) has existed due to water pumping in the Jeremenko pumping shaft (see Fig. 3) and an altitude of -483 m below sea level (approx. 680, m below surface) in the Zofie pumping shaft (see Fig. 3). The main reason for this is to prevent water over flooding into the Karvina sub-basin due to connection of all sub-basins through tectonic structures, as well as underground openings.

The times of flooding in the Ostrava and Petrvald sub-basins were predicted according to the volume of mine out-coal seam, the coefficient of compaction of goaf areas, the volume drained detritus horizon and the occurrence of alternated Carboniferous rock mass layers [11,12].

The preparatory phase preceded underground water pumping termination in every active mine in the Ostrava sub-basin. There is a scheme of flooding for individual mines given in Fig. 4 [17], where the state of flooding in 2015 is also presented [12].

The phase of mine flooding started in June 30, 1997, but the partial flooding of terminated coal mines started earlier in 1991. Water from the Sverma mine, one of the first terminated mines, overflowed to the Odra mine. The first measurement of the water level in the Jeremenko shaft was on July 1 1997 (-781.7 m below sea level). A water level of -390.8 m below sea level was reached in 2001 when the pumping started. The water level in the Jeremenko shaft is preserved from -371.5 to -389.5 m below sea level, i.e., approx. 39.5 to approx. 58 m, respectively, below the deepest connection to the Ostrava and Petrvald sub-basins.

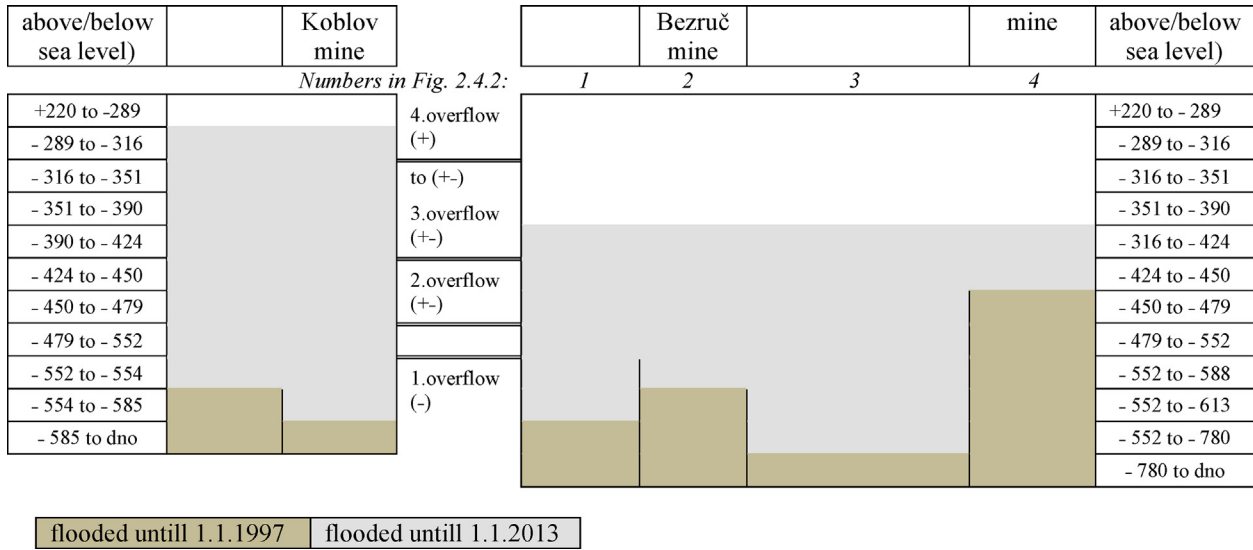


Fig. 4. State of mine flooding in Ostrava sub-basin (in 1997 and 2015) [12].

The first evaluation of mine flooding prognosis comes from the principles of communicating vessels. The water level was predicted to be the same in all the sub-basins. The water levels were monitored in more places than just the Jeremenko shaft (two in the Ostrava pond and one in the Odra pond). Measurements showed that the water level was different in some mines due to the hydraulic resistance between the Ostrava and Odra ponds. It was proved that differences between the Ostrava and Odra ponds caused the 100 m difference in water

level between them. It is noteworthy that the water level was higher in the Odra pond (−585 m below sea level) than in the Ostrava pond (−760 m below sea level, see Fig. 4). Furthermore, the increase in water level was caused by natural flooding in 1997, which overflowed shafts in the Odra and Privoz mines and caused a steep increase in the water level of approx. 70 m.

The rise of the water level in the Ostrava and Petřvald sub-basins is presented in Fig. 5. The irregular shape of the water level curve is impacted

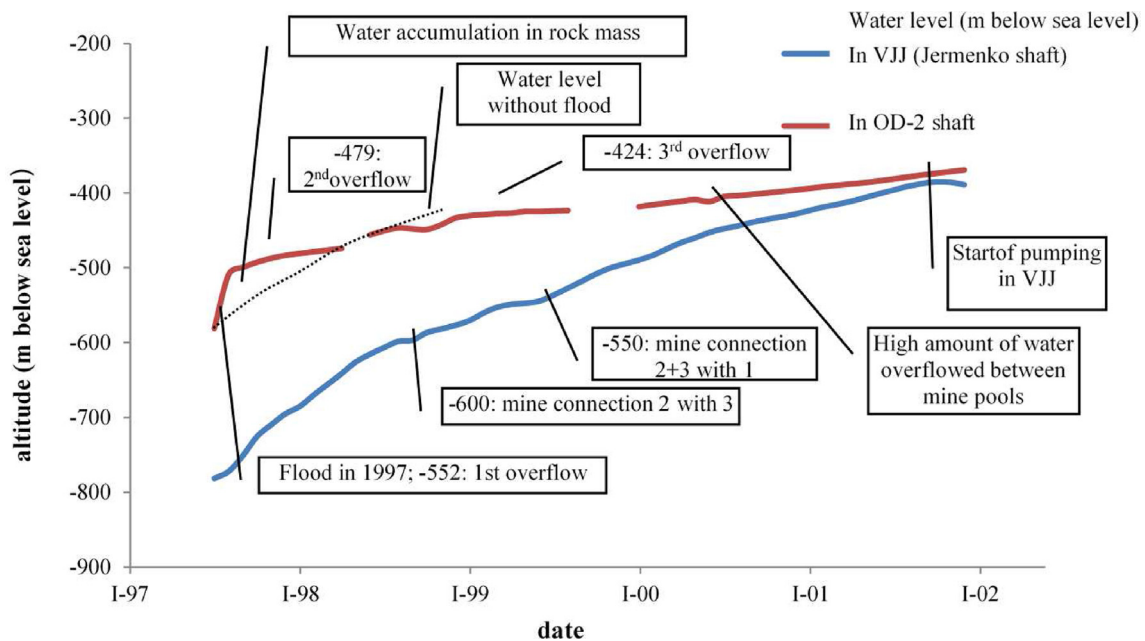


Fig. 5. Water level monitoring in Jeremenko (VJJ) and OD-2 shafts from 7/1997 to 12/2001 (12).

by volume changes in the mining of coal seams, e.g., the flattening of the curve of the Jeremenko shaft from -600 to -550 m below sea level, which can be connected to mining claims between the Bezruc and Trojice mines and the Jeremenko, Zarubek and Alexander mines. The impact of natural flooding from 1997 is evident on the OD-2 curve, where the impact of the first connection between coal mines at an altitude of -552 m below sea level is completely removed. This contact was qualified as a “–“ [12], meaning that natural flooding was also not registered in the area. This means that there are two evident places in the curve with temporarily decreasing water levels (September 1, 1998, (-448 m below sea level) and June 1, 2000 (-441 m below sea level)), which could be the impact of overflowing the same water volume from the Odra to Ostrava pond after increasing the water level by 30 m respect to 15 m above the interconnection altitude. The flattening of the OD-2 curve occurs after increasing the water level to the third connecting level (3 months, the same water level). Additional details are available in [12].

The water level curve from OD-2 (Zofie shaft) could be interpreted without natural flooding in 1997 since the increase in the water level has the same slope as in the Jeremenko shaft (VJJ in Fig. 5), as marked by the dotted line in Fig. 5. Steep and short (days) increases in water volume saturated the goafs unevenly but not fully. The Carboniferous rock mass was not saturated fully, and the full saturation of the rock mass continued, with the water level in the Zofie pumping shaft (OPD-2 in Fig. 5) increasing slower than the water level in the Jeremenko pumping shaft. The water level curve increases steeply after the full saturation of the rock mass and after exceeding the second level of connection by above approx. 30 m (-448 m below sea level), as a consequence of the connection between ponds and increases the amount of water flooding into the Ostrava pond. This situation repeats when the water level is increased by approx. 15 m above the third connection level (altitude of -424 m below sea level), with a steep increase in water level in the Jeremenko shaft and a decreasing water level difference between the Odra and Ostrava ponds. The water flooding in water level connections 2 and 3 decreased. Flooding between the Odra and Ostrava ponds was terminated on water levels 2 and 3. After that, the pumping of water in the Jeremenko shaft started (as described below).

Flooding of the Petrvald sub-basin is monitored only in the Zofie water shaft (see Fig. 3). Mining was terminated in the Petrvald sub-basin in 1999. The period of mine flooding terminated in October 2001 when pumping began.

The pumping regime is the same as in the Jeremenko shaft but interrupted. All mines in the Petrvald sub-basin are considered a hydraulic connected system (communicating vessel system). The pumping volume from the Petrvald sub-basin is stable on the level at approx. 38 l s^{-1} . The pumping volume from the Ostrava sub-basin is stable on the level at approx. $170\text{--}200 \text{ l s}^{-1}$.

6. Registered seismicity

During the flooding period of the Ostrava and Petrvald sub-basins (1994–2001), there were few critical situations recorded in the light of induced seismicity as well as in the period of preserving the water level at the stated altitude (2001 to date).

Due to flooding of the Ostrava and the Petrvald sub-basin low seismic activity was registered (Fig. 6). Eleven seismic events with an energy of approx. 10^3 J and four of approx. 10^2 J have been registered in the flooding period. Seismic events were not registered on the surface. Two seismic events were registered outside of the mining claims; three were registered in the mining claim of the Hermanice mine; one was registered in the mining claim of Slezka Ostrava III, and twelve were registered in the mining claim of Radvanice. According to the valid legislation, only high-energy seismic events are evaluated in detail (seismic events with energy of approx. 10^4 J and higher). High-energy seismic events were not registered during the period of mine flooding.

During the three periods of water level preservation at the stated altitude, low seismic activity was registered, specifically in the Petrvald sub-basin (Fig. 7). If we do not consider seismic events again at the border between the Petrvald and Karvina sub-basins in the area of the Michalkovice structure, only 15 seismic events have been registered: nine with energy up to 10^2 J ; five with an energy of 10^3 J , and one with an energy of 10^8 J . In terms of location, two seismic events were registered outside mining claims, six were in the mining claim Radvanice and one was registered in the mining areas of Privoz, Slezska Ostrava I and Petrvald III. During the period of water preservation, there was one energetic seismic event (energy of 10^8 J) that, according to current legislation, has to be analysed in detail. This seismic event was recorded by the Czech Regional Seismic Network as an earthquake (magnitude 3.5, 12 December 2017) [18]. The relationship to the mining activity in the Ostrava region, as well as to the flooding of the Ostrava sub-basin, has not been studied until now. This possible relation to the Ostrava sub-basin flooding is studied here.

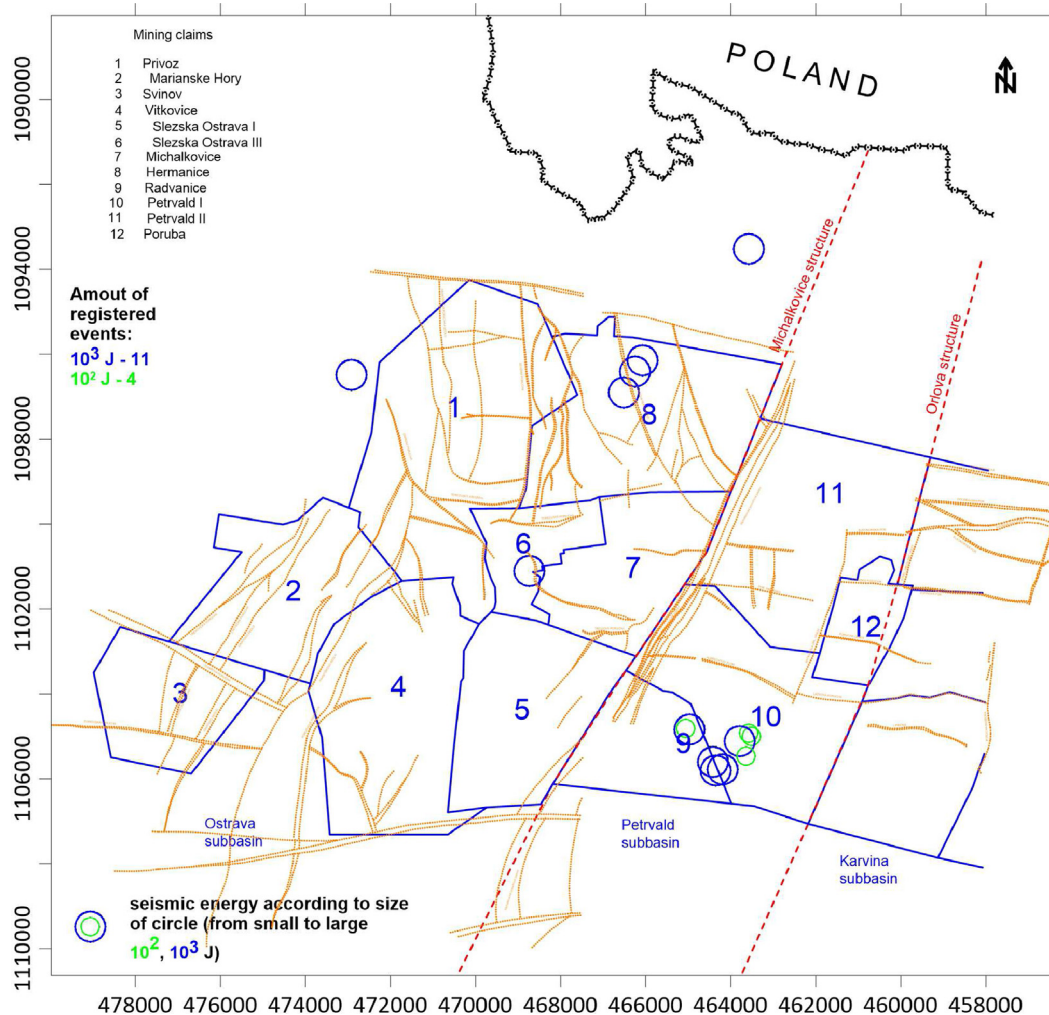


Fig. 6. Registered seismic activity during flooding period of Ostrava and Petrovald sub-basins.

7. Observed surface subsidence

The development of surface subsidence after the closure of mines in the Ostrava sub-basin can be evaluated from the results of precise levelling. After closing the mines, only the levelling of the main lines was observed. These lines lead from the non-mined area and contain points that are part of the Czech state levelling network. The height accuracy of the observed points is 2 mm and was determined by adjustment of the levelling network.

Ground surface subsidence depends on many factors, which include the mechanical properties of overlying and surrounding rocks. The time of surface subsidence during and after mining can be divided into three stages, as discussed below.

The first (initial) stage of subsidence is the time from the manifestation of the first subsidence up to the time of intensive subsidence. This time does not

include the time necessary for the first movement caused by mining to be shown on the surface. The duration of this stage depends, in addition to the given factors, particularly on the speed of the advance in mining work. The time necessary for the first subsidence to be shown on the surface depends particularly on the speed and depth of mining. In the first initial subsidence stage, the surface points subsidence reaches 5% of the total subsidence.

The second (main) stage is intensive subsidence. During this stage, the subsidence of surface points reaches 70–80% of the total subsidence. This stage is the most dangerous for surface objects and installations due to rapid changes in the deformation values of the surface. With increasing mining depth, the subsidence velocity decreases because the subsidence is distributed over a longer period. The

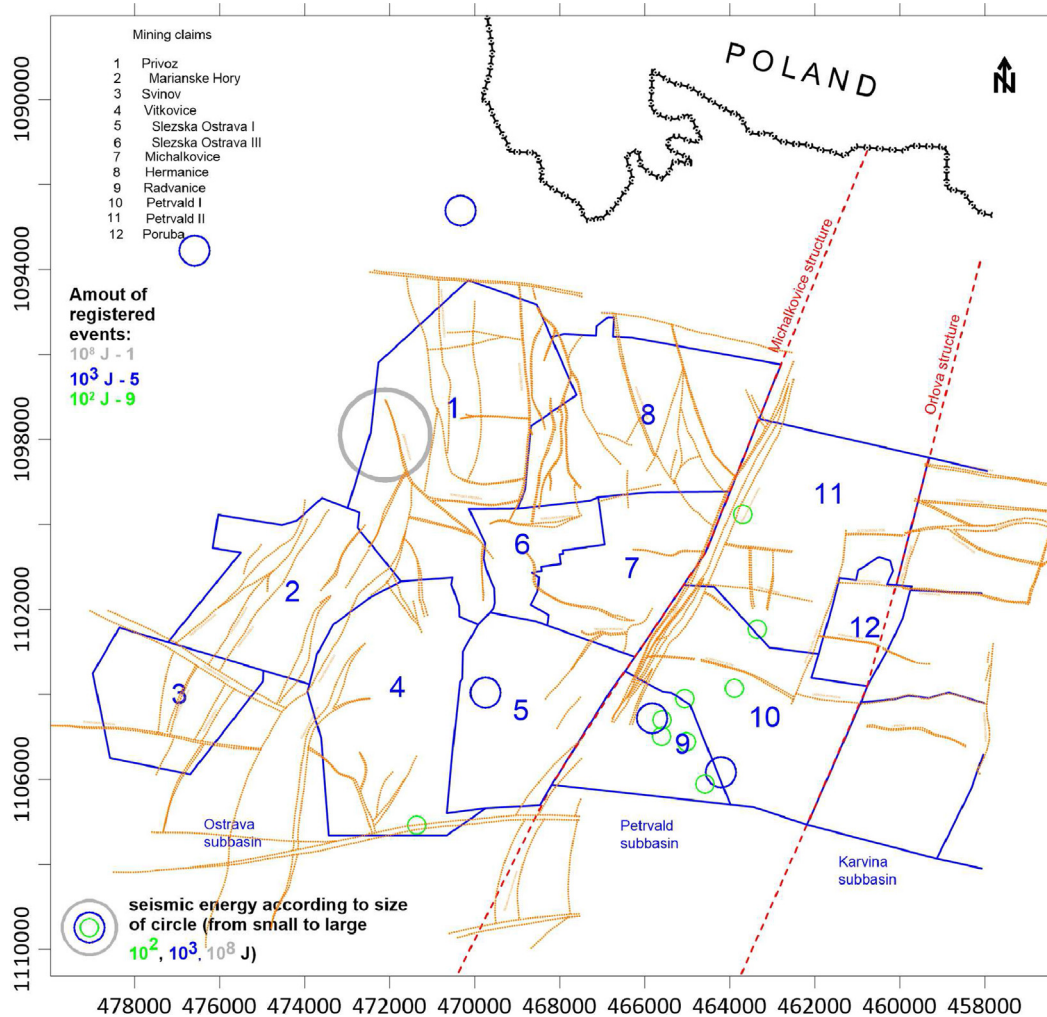


Fig. 7. Registered seismic activity during pumping period in Ostrava and Petrovald sub-basin.

boundaries between the individual stages become indistinct.

The third stage is fading-out, where the movement is stabilised. This stage cannot be well defined in terms of time because subsidence at the final stage gradually becomes smaller, so it cannot be measured or detected by measurement anymore. It can be stated that, theoretically, they last for an infinitely long period. Practically, however, it is possible for every coalfield to define the time after the elapse of which it is possible to neglect subsidence from a technical perspective. Subsidence at the stage of fading out is small, and its course is so slight that it does not cause damage to surface objects and installations. According to the mining experience in the Ostrava-Karvina coal district, the surface movements stabilise in 3–5 years.

In order to present the surface subsidence in connection with the flooding of closed mines, two

observed points were selected to document the surface subsidence rate during the mentioned period (Fig. 8). The timeline of Fig. 8 is divided into periods of longwall mining, flooding of the Ostrava sub-basin and pumping. The graph of the subsidence curves of surface points 23 and 30.1 further shows the longwall mining time at the effective area of these points, during which the mining has a direct effect on the subsidence in surface points. This period, which lasted until 1991, belongs to the second stage of intensive surface subsidence. In the years between 1991 and 1994, longwall mining took place outside the effective area of the observed points. This period belongs to the third stage of surface movement stabilisation. The periods of flooding and pumping followed. During this period, the stopping of subsidence and the subsequent slight ground surface uplift were observed at some surface points, as seen from the curve of point 30.1.

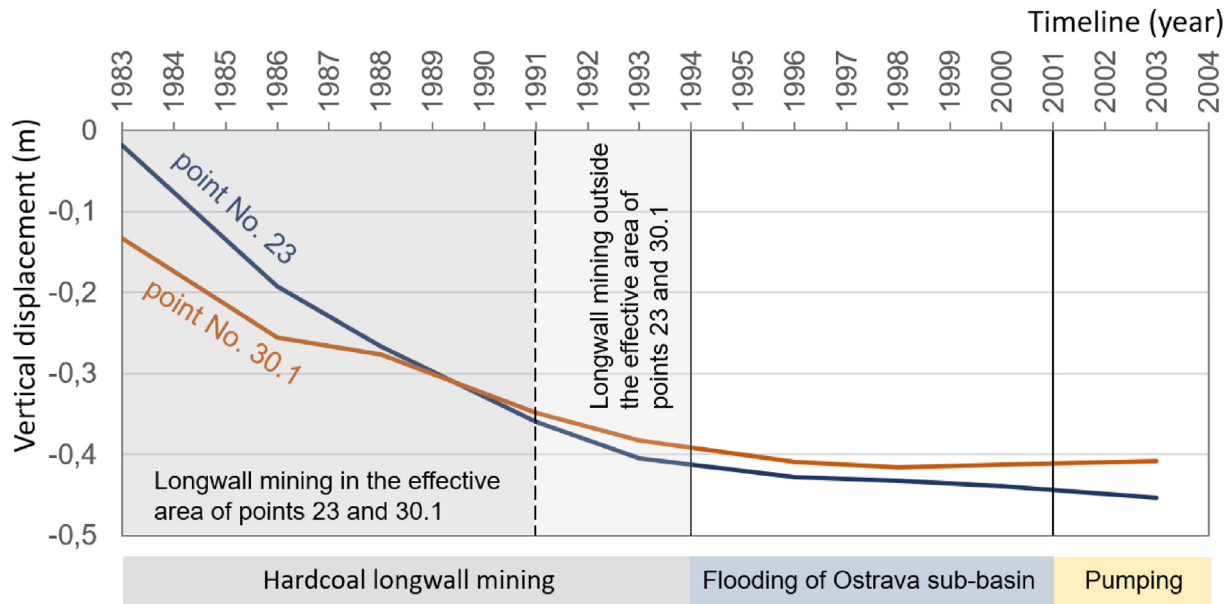


Fig. 8. Surface subsidence example of two selected points in the Ostrava sub-basin.

Other surface points continued to show an increase in surface subsidence, even at the time of pumping, as can be seen from the curve of point 23. In both cases, however, these are small movements: in the case of subsidence up to 50 mm, and in the case of ground uplifts, up to 12 mm. The mentioned values of surface subsidence and ground uplift characterise the highest achieved values in the period from 1996 to 2003.

8. Discussion

The observed subsidence was evaluated in terms of the differences in the measured heights at the surface points, which were obtained by a precise levelling method. The height accuracy of the monitored points was evaluated from the adjustment of the levelling networks and set at 2 mm. This value is considered the root mean square error of which double (4 mm) presents the confidence interval interface. If the values of the movements exceeded this, they are considered to be proven. The mentioned maximum achieved values of surface subsidence (50 mm) and ground uplift (12 mm) can therefore be considered proven. The results of the observed surface movements will/may be used to evaluate the relation between surface displacements and rising water levels in the individual underground pond. This evaluation will be possible only on the basis of detailed elaboration of the area and water level height in the individual underground ponds, which will be elaborated within the PostMinQuake project.

The observed induced seismicity during the flooding of mines in the Ostrava and Petrvald sub-basins area is low when we compare it with other flooded coal mining regions, e.g. the Ruhr area and Ibbenbüren in Germany [6], and the Provence region in France [5]. There were no recorded incidents on the surface connected with mines flooding in the Ostrava and Petrvald sub-basins. The main reasons for low seismicity during mine flooding can be considered as follows:

- the water level in flooded coal mines is preserved 600 m below the surface for the Ostrava sub-basin and 680 m below the surface for the Petrvald sub-basin due to overfolding water to the active part (Karvina sub-basin);
- only thin coal seams (prevailed thickness from 40 to 110 cm) were mined in the Ostrava and Petrvald sub-basins;
- occurrence of thick competent rock layers (from 10 to 100 m) is missing in the Ostrava and Petrvald sub-basins;
- possible lower detection ability of seismic networks designed for different reasons (e.g. rock-burst prevention in the Karvina sub-basin) should be taken into account.

In contrast, there were recorded earthquakes close to the mine area of the Ostrava sub-basin (12 December 2017) during the period of preserving water at the stated level. A possible relationship with previous long-term mining activity and flooding of part of the rock mass should be studied in detail.

9. Conclusion

The induced seismicity was recorded during the periods of flooding and pumping in the Ostrava and Petřvald sub-basins. Due to the specific natural and mining conditions, low seismic activity was recorded. From the first point of view, it is connected with the small thickness of coal seams and the occurrence of a small amount of competent rigid rock layers with a high thickness (different than in the Karvina sub-basin or in the Morcinek mine), as well as with a great depth of mining. Very important is (differently than in any other mining regions) that flooding of mines was interrupted here at the stated altitude due to overflowing water to the active Karvina sub-basin. It means that only approximately one half of the exploited rock mass was flooded up until now. Another reason could also be a lower detection capability of seismological monitoring systems outside the Karvina sub-basin.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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Conflict of interest

The authors declare no conflict of interest.

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