DNIPRO UNIVERSITY of TECHNOLOGY 1899

Mining of Mineral Deposits
ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)
Journal homepage http://mining.in.ua
Volume 12 (2018), Issue 2, pp. 34-46

UDC 622.831.6 https://doi.org/10.15407/mining12.02.034

GEODETIC AND SEISMOLOGICAL OBSERVATIONS APPLIED FOR INVESTIGATION OF SUBSIDENCE FORMATION IN THE CSM MINE (CZECH REPUBLIC)

V. Kajzar[1*]

[1]*Institute of Geonics of the Czech Academy of Sciences, Ostrava, Czech Republic*
**Corresponding author: e-mail vlastimil.kajzar@ugn.cas.cz, tel. +420596979342*

ABSTRACT

Purpose. Undermined areas are affected by the creation of subsidence depressions due to long-term underground mining. In general, different geodetic methods are applied to obtain further information needed to determine the spatial development of the formation of a subsidence depression.

Methods. Application of these surveying methods enables us to investigate spatio-temporal changes of landscape relief in detail. Although the development of surveying technologies is in progress at present, conventional geodetic methods are still in use. Nowadays Global Navigation Satellite System (GNSS) surveying is mostly used for obtaining the actual degree of relief affection in undermined areas. Considering that during coal extraction induced seismic events are observed underground and on the surface, some seismological methods for their parameters determination were applied, e.g. foci location of induced seismic events, their classification by units of magnitude and by released seismic energy, frequency energy distribution, construction of Benioff graph and its derivation for assessment of adjacent working endangerment.

Findings. The results of the assessment and analyses of spatial data demonstrate the real development of the subsidence depression under study and the relief changes of the landscape during the investigated period, respectively.

Originality. It was recognized that all methods applied in this study represent very helpful tools for surveying subsidence depression and simultaneous monitoring of seismic activity development on an undermined area.

Practical implications. Based on obtained results it is possible to perform a comparison of current subsidence dimensions with the original rate of affection.

Keywords: *Ostrava-Karviná coal basin, subsidence depression, surveying methods, seismic monitoring, displacement*

1. INTRODUCTION

The problems associated with subsidence depression have been recognised for many years, e.g., Crane (1931) and Knothe (1953), and currently, a large volume of published work has summarised in detail the results of investigation into this phenomenon, e.g., Yarbrough (1983); Holzer (1984); Whittaker & Reddish (1989); Bell, Stacey, & Genske (2000); Blodgett & Kuipers (2002); Bell & Donelly (2006); and Hyndman & Hyndman (2011). This has included many papers oriented to the research of subsidence depression occurring in coal mines in the Upper Silesian Coal Basin (USCB), e.g., Neset (1984); Dulias (2003); Bláha, Doležalová, Müller, & Skopal (2006); Doležalová, Holub, & Kaláb (2008); Kajzar, Doležalová, Staš, & Souček (2009); Bogusz & Mendecki (2011); Idziak & Dubiel (2011); and Kajzar (2011).

Based on the information obtained from various streams of literature, in principle, two different causes of subsidence depression can be documented. Firstly, the interaction of natural forces, and secondly, man-made underground activities.

1.1. Subsidence depression caused by the interaction of natural forces

Subsidence which occur due to the interaction of natural forces include sudden collapse caused by the long-term action of groundwater containing a weak carbonic acid solution, which dissolves the calcium carbonate sedimentary beds of limestones and dolomites underground. This chemical process usually leads to the formation of conditions of an extensive karst area with caves, where the occurrence of subsidence depressions is frequently observed. Subsidence also exists due to the burning down of coal seams, where any supporting body for the roof collapses after a fire, as described, e.g., by Kuenzer et al. (2007) and Stracher (2007).

1.2. Subsidence depression caused by man-made underground activities

The second most common and prevailing type of subsidence depression formation is created in the course of man-made underground activities. It should also be taken into account that similar geological and geomechanical conditions for subsidence creation occur when oil and natural gas are withdrawn from their deposits near the surface (Geertsma, 1973). At this time, fluid pressure is reduced and therefore, the pore spaces are gradually compressed and the sedimentary layers begin to compact with less volume. Thus, consequently, vacant volume inversely prepares conditions for the development of subsidence depression on the surface. According to the statistics, subsidence depressions have most frequently been found in areas where underground extraction of selected raw materials in the past or at present has been conducted. These raw materials include, e.g., salt (Gisotti, 1991), gypsum, sulphur, and various ore-bearing rocks. However, the predominant group of these raw materials is represented by brown and hard coal. Considering that we are dealing with problems of subsidence which occur in the landscape above active mines situated in the eastern part of the Karviná region, then subsidence can originate, simultaneously, with the mining operation passing through. Underground mining, especially with thick coal seams, is usually associated with the gradual creation of subsidence depressions on the surface above the undermined area. The depressions which occur though this worked out space are spontaneously filled by rubbish when caving methods or low-pressure stowing are used. Due to the compressibility of the backfill during an undefined time interval a vacant space occurs, which is subsequently slowly filled up by sinking material of the overlying strata and thus the beginning phase of subsidence has been created. Lately, the solving of this problem has been taken seriously from the viewpoint of environmental protection in order to reduce the influence of coal mining on the surface relief, surface structures and dwelling houses above.

It is obvious that the intensity of coal extraction has a dominant influence on the creation of subsidence depression and by extension develops in close connection with the advance of working faces. All changes of the excavated space underground are step-by-step reflected in overlying strata up to the surface. The area afflicted with the forming depression will exceed several folds the extent of the exploited space and the site of the centre of the maximum sinking roughly above the excavation area. While towards the margins, the subsidence depression will be shallower.

The aim of this study is to present new information related to the use of geodetic methods like levelling and GNSS surveying, and the implementation of seismological measurements in the process of surveying the subsidence formation in the CSM Mine (Czech Republic).

2. DESCRIPTION OF THE LOCALITY

2.1. Area of interest

The Ostrava-Karviná Coal Basin (OKCB) is part of the Upper Silesian Coal Basin (USCB), representing roughly a third of the whole area which is mainly situated in Poland. The Czech part of the USCB mining area is situated in the north-eastern part of the Czech Republic and includes three partial regions of mining, i.e., Ostrava, Petřvald and Karviná mining fields (Holub, Holečko, Rušajová, & Dombková, 2012). Mining started in the OKCB more than 200 years ago in the Ostrava region, then mining shifted to another mine field at Petřvald. Around 1980, mines in both regions were gradually terminated, while increasingly new mining activities started in the Karviná region.

At this time the whole coal field was divided into eight mines, each subdivided into several mining blocks limited by tectonic faults. Later, some of these mines were gradually closed, several were integrated, and after restructuring of the new mines, four mines currently remain active. For our experiments field work blocks Nos 0 and 1 of the CSM – North Mine were chosen. The study area is depicted in Figure 1.

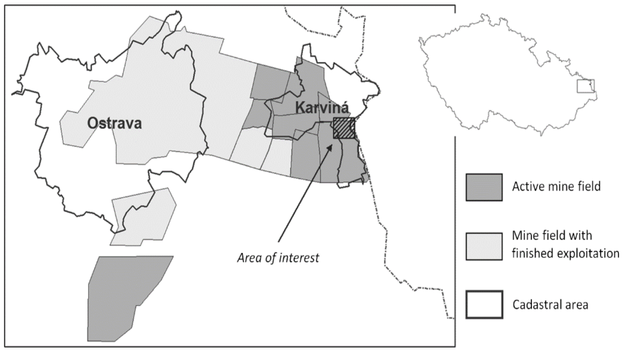

Figure 1. Spatial demarcation of the Ostrava-Karviná mining area

2.2. Brief geological situation of the coal deposit

The sedimentation cycles started in the latest Upper Carboniferous stage and consist of two essential Carboniferous formations, i.e., the Ostrava and Karviná series. The coal bearing strata belong to the Namurian A, B and C, which are followed with Westphalian A. The evolution of the sedimentation basin was seriously affected during the orogenic motions in Cadomian, Variscan and Alpine structural stages. These motions caused the disruption of sediments in the coal basin, the orientation of which is roughly east-west and north-south. Tectonic faults due to disruption became demarcation lines between individual mining and tectonic blocks in individual coalfields. The representative rocks of the geological profile are mostly sandstones, conglomerates, claystones, siltstones and coal seams, with variable thickness and physical properties in individual layers. The uppermost part of the cover in the area of interest is represented by impermeable Miocen clays and quaternary sediments.

2.3. Local mining conditions and tectonic pattern

Tectonic lines in Figure 2 indicate the anticipated course of tectonic structures at the level of coal seam No.36a. At the beginning of October 2006, exploitation started of the first of the planned longwalls

(No.361000). However, due to the unfavourable geological situation, the working face had to be cut down and in June 2007 the coal extraction was terminated. For the same reasons, the second planned face was not opened. In May 2007 mining started in coal face No.293102, which was situated in seam No.29. After exploitation of this coal face an interruption, which lasted eight months, was accepted. From the beginning of 2009 a reopening of mining in two coal faces was realised, i.e. face No.362000 in the seam No.36b, which was followed by face No.300102 in the coal seam No.30. Since June 2010 mining in this area has been terminated. Based on evaluation of the geological properties of rocks and the geomechanical situation in the CSM Mine, i.e., according to the regional prognosis, the tectonic block "0" situated in the "sedlové" layers, was indicated as the layer predisposed to rockbursts occurrence.

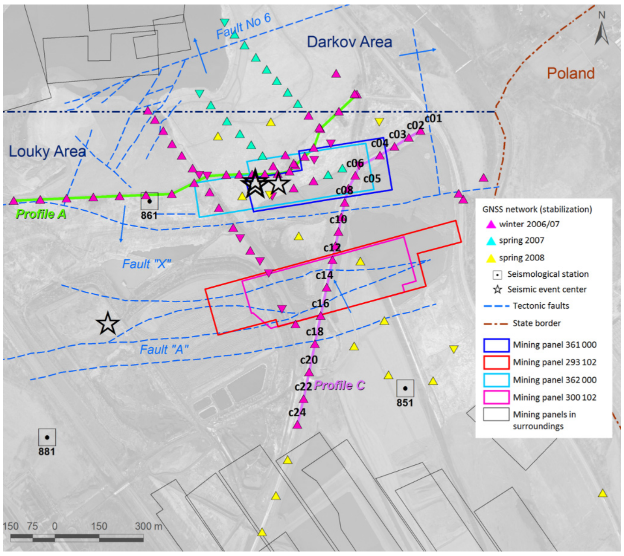

Figure 2. Schema of longwall positions planned for mining within the time period 10/2006 – 12/2010, spatial spreading of observation points GPS system and deploying of seismic stations and foci of seismic events ($E \geq 10^4$ J) in the investigated area

This generally complicated situation is documented by the geological section of the coal deposit shown above. The space of interest displayed in its vertical cross cut is intersected by three tectonic faults as shown in Figure 3:

– fault "X" – has a dip-slip character, the thickness of its shear zone is roughly 20 – 50 m, with a length of the fault of about 350 m and dip roughly 60°;

– fault "A" – which corresponds to a pronounced dip-slip tectonic fault with the length of the fault of about 350 m, the dip of which is about 60°, but the thickness of shear zone is considerably larger than the thickness of fault "X";

– fault No.6 – is a less marked fault situated in the northern part of the investigated area;

– moreover, there exists another marked fault denoted as the "Těšín fault" situated in the eastern part of the mining field, which follows the Czech-Polish border and which is not displayed in Figure 3.

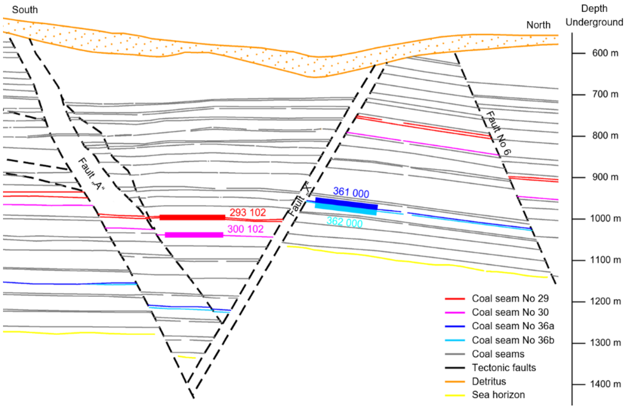

Figure 3. A simplified vertical cross cut through the area of interest

2.4. Influence of underground mining on surface relief

The influence of deep coal mining shows up in the landscape neighbourhood not only at the time of mining but also when mining is terminated. These influence can be distributed according to the measuring of surface changes to following groups:

– motions and deformations of the landscape;

– various vibrations such as the manifestation of induced seismicity and natural seismic events, i.e., rockbursts and earthquakes, respectively;

– anthropogenic impact on the relief of landscape due to dumpings of extracted material, reservoirs for mud coal;

– further consequences of mining activities, e.g., hydrological changes, underground flow of gases etc.

Apart from the influences of deep underground mining on the environment, interactions with several additional very important factors should also be taken into account, as mentioned, e.g., by Neset (1984):

1. Physical and mechanical properties of rocks – physical-mechanical properties of different types of rocks determined in laboratory conditions cannot be automatically accepted for further premeditation related to properties of the complex rock massif in situ. This assumption is based on the fact that the variability of physical and mechanical properties of rocks with depth is generally known. In any case, this is the reason why the mathematical modelling of depression formation by using only theoretical values of the parameters of a given medium is a target, the attainability of which is not very often unambiguous.

2. Geological conditions of deposit – influences of mining in overlying rocks depends on the geological structure of rock mass, i.e., stratigraphy, tectonics, hydrology, structural geology etc. The shear zones in the immediate roof of the overlying rocks are able to create a limitation of the range of impact zones. Good knowledge of geological conditions and properties of surrounding rock material are the basis for deliberations concerning the character and size of expected motions.

3. Size of deposit – when different bulky deposits are compared, it can be stated that the bulkier the deposit is, then the stronger the motions usually manifested in the immediate roof and on the surface will be.

4. Depth of the deposit beneath the surface – it is obvious that due to an increasing depth of deposits, the reach of mining influences will frequently be more extensive. When estimating the influence of deposit depth to the size of faults and deformations, the thickness of sedimentary cover must also be taken into account.

5. Methods of raw material mining – the extend and the shape of the subsidence depression on the surface also depends on the method of mining, i.e., where mining without filling, caving or low-pressure stowing is used, an important factor represents the compressibility of the backfill material, which leads to different vacant spaces underground for the creation of a subsidence trough on the surface.

6. Induced seismicity – one of the negative consequences of man-made activity in the Ostrava-Karviná coal mines is the occurrence of induced seismic events like rockbursts and mine shocks. These phenomena are incidental of deep level mining, because during coal extraction some changes in the stress-strain equilibrium are generated in the massif, which are usually followed by brittle crushing of rock and coal material (Jiránková, Staš, Kajzar, & Doležalová, 2013). Here, the rockburst is characterised as the sudden release of stored elastic deformation energy in the rock which is changed to kinetic energy that inflicts the process of material disintegration underground.

2.5. Mine damages

Deep coal mining unfavourably affects surface structures and residential houses situated mainly above the currently mined or abandoned part of the deposit, where mining operations were terminated in the past. It can generally be stated, that in the course of surveying the consequences of mining influences, two basic and important factors must be considered; the first represents the time factor of the dynamic processes in the rock massif, while the second factor is connected with the coalface advance, which exposes the structures to dynamic changes. These changes are denoted in professional terms as: displacements, subsidence, deformation, angular rotation, extension or slide. To minimise the unfavourable conditions for surface structures some measures underground can also be applied, e.g., by preserving various safety pillars (shaft, cross cut etc.).

3. SURVEYING METHODS FOR LANDSCAPE CHANGES OF RELIEF

Selection of the method of measurements depends mainly on:

– the purpose and extent of these measurements;

– the amount of expected displacements;

– requisite accuracy of temporal, technical and field conditions (Schenk, 2005).

Although the development of surveying technologies and approaches are in progress at present, the surveying of displacements and deformations of surface is in practice performed mostly by applying only conceptual geodetic methods of direct surveying, especially the method of levelling. The practical application of the levelling method is aimed at determination of the super elevation between two points. It is possible to evaluate the development of subsidence from a time series of realised measurements. The accuracy of these measurements varies within the limits of several millimetres. An important requirement of using this method is to connect measurements of the undermined area with the stable area of the unaffected region, which is not only time consuming but often introduces inaccuracies.

Selected localities cross several levelling profiles. Regular height measurements are performed by the mining company. A half year interval between measuring campaigns and also the location of these profiles does not allow accurate determination of the temporal evolution of the subsidence in the context of the mining process. The resulting data can be used only for long-term monitoring of subsidence formation in the broader surroundings.

For recording the spatial changes of the undermining surface area not only during the actual mining, but also in the periods between individual longwall mining and during the final period after completion of mining activities, GNSS methods are currently being used successfully. The GNSS is a world-wide navigation service, which has the advantage of satellite spatial determination of various subject positions. The primary task of the conception of GNSS is to determine the position of both static and moving objects. The advantage of GNSS compared with traditional geodetic levelling, which allows recording of height changes only, is the ability to provide spatial coordinates of surveyed points. Another advantage is the ability to quickly connect the undermined area with the stable area that is not affected by mining.

When a region of interest is chosen for this method, the distribution of individual points always depends on the size and shape of the expected subsidence depression. Therefore, all efforts during the preparation of the planar distribution of individual points are aimed on the one hand at identifying the anticipated centre, bottom, slope and margin of the depression, and on the other, at identifying the area beyond the influence of mining.

In order to monitor the creation process of the subsidence depressions above exploited coalfaces using GNSS methods, namely the NAVSTAR GPS (Global Position System, usually denoted as GPS). Since 2007, the observation station has, in the final stage, counted more than one hundred points. The GPS is a service with worldwide coverage by satellites for the autonomous determination of the spatial position of objects. However, for special and scientific applications the accuracy obtained is within the range of tens or units of millimetres. In geodetic practice several verified methods are applied using signals of GNSS, namely the static method, fast static method (pseudo-static), method Stop and Go (semi-kinematic), kinematic method and kinematic method in real time. For surveying of displacement and deformations, the fast static method was chosen. This method is a modified variant of the static method. While the static method requires measurements for several hours or sometimes even several days, the fast static method or GPS methods need approx. 10 – 20 minutes.

To monitor the locality of interest the fast static GNSS method was chosen. Observations were carried out by two Leica GPS System 1200 devices. One of the devices was used as a field rover to record the positions of points of the observation station. The observation time was at least 10 minutes at every point. The second receiver was applied as a reference station and was permanently positioned above a trigonometric point where simultaneous continuous recording of its spatial position was performed. This point belongs to the national geodetic network and is situated outside the considered effects of mining, i.e., a few kilometres away from the observation network. The measurements were performed from November 2006 to March 2011. To retain gradual development of surface changes an interval of five weeks was considered for repeating measurements. After completion of selected mining activities, the time interval between individual series of repeated measurements was extended. Spatial coordinates of monitored points were evaluated during post-processing using the software Leica GeoOffice, and exported to the coordinate system WGS-84 and Czech national system of S-JTSK. The accuracy (RMS) of the static observation with subsequent post-processing is declared to 0.005 m + 0.5 ppm in the horizontal and 0.010 m + 0.5 ppm in the vertical position of the point (Leica GPS1200 Series Technical Data, 2018). The average deviation in determining the spatial position of the monitored points varied in the interval from 0.01 to 0.03 m. It is depended on the distance between both receivers, the current constellation of satellites and the subsequent use of accurate ephemerides during post-processing.

Further information needed for determining the spatial development of the shape and range of the subsidence depression necessitated the use of remote sensing methods, e.g., aerial photogrammetry and radar interferometry, however, these methods are not the subject of this paper.

4. ASSESSMENT OF CHANGES OF THE LANDSCAPE RELIEF USING GPS DATA

Data obtained by GNSS are used as a suitable source of input for analysis of surface changes of the surveyed areas. With repeated use of this method and also because of suitably stabilised points from the observation station in the form of profiles and scattered points it is possible to evaluate the ongoing development of subsidence and horizontal displacements across the entire area.

The modern geo-informatics software accompanied by purpose-built software tools (scripts, extensions, applications) allowed effective work with the obtained data. These tools allowed the performance of a very interesting spatial analysis based on the acquired data. The remainder of this paper will attend to analysing the temporal evolution of point subsidence, the subsidence in line profiles, the spatio-temporal subsidence modelling and the surface horizontal displacements. In addition, further analyses were also carried out, including analysis of the time-dependence of the surface changes on the progress of the exploitation, a comparison with the official calculated predictions and the prognosis of future subsidence development.

4.1. Comparison of results obtained from levelling and GPS measurements

Results of levelling measurements are a suitable tool for verifying the accuracy of GNSS data. As aforementioned the method of geometrical levelling is a very precise surveying method applied for the determination of height changes in the undermined area. Their availability allows therefore, in the first phase of the problem solution, the comparison and verification of the accuracy of realized GPS measurements. The values of the measured levelling profile of the levelling network denoted as CSM were entered into the comparison. A part of this profile coincides spatially with one of the GPS profiles, profile P. Figure 4 displays values of subsidence increase derived from both measuring methods starting at zero value in November 2006. The first incremental step was the subsidence situation up to May 2007, while the second step was the state up to November 2007.

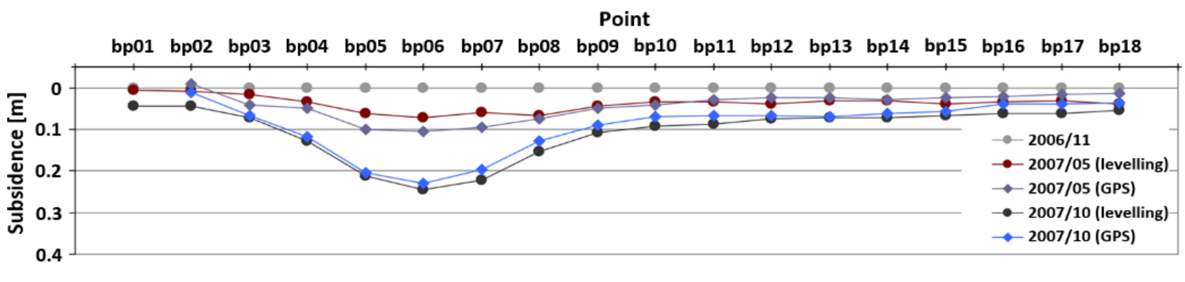

Figure 4. Comparison of results obtained by using the method of levelling and GPS measurements

The mutual measure of analogy in depression development determined from the evaluation of both methods is very high. Only moderate mutual deviations occurred, which might have been due to:

– non-identical positions of the input points;

– temporal interpolation of GPS values;

– inaccuracies of GPS measurements or mistakes of levelling;

– changes of the access point of levelling or GPS reference point etc.

Regarding the numerous influencing factors and the surprisingly good similarity of the determined values of the depressions enabled us to estimate that the applied GPS method for the purpose of surveying elevation changes on the undermined area were fully satisfying.

4.2. Analysis of point subsidence development in time

The time development of the subsidence of individual points, which was calculated on the basis of their elevation changes, was important for formatting a subsidence depression, because it characterised the degree of changes in the vertical position among individual measurements, and the speed of these changes.

The changes are characterised by a curve denoted as depression curve displayed in Figure 5 by black dots, which represent a running change of elevation values for selected point c10. The speed of changes depends mainly on the advance of mining in individual coalfaces. The shaded rectangles indicate the time of coal exploitation in individual longwalls.

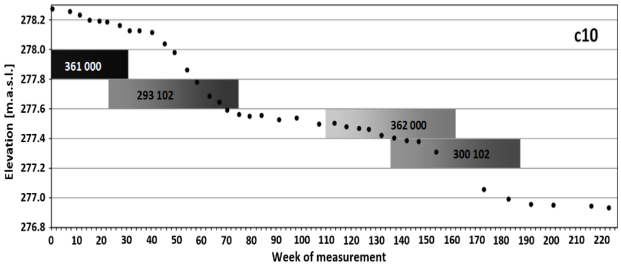

Figure 5. Temporal development of elevation changes of the point c10

An overview of resulting depression curves measured on the points c08, c10, c12, c14, c16 and c18 along profile C during coal extraction of coalfaces 361000 and 293102 is shown in Figure 6. Presented graphs document that all phases of subsidence formation are obvious, i.e., slow decrease of depression curve followed by a steep increase, which later passes to a stage of stabilisation, until finally follow the fading of the whole process. Different developments of depressions were shown, e.g., the measure of decrease does not depend only on the advances of mining but also on the spatial positions of points within the mined area. By analogy the measure of depressions depends on the position of the surveyed point against the mined longwalls, the thickness of seams, the depositing depth of the mined block of coal, and on the actual geomechanical situation underground. In graphs situating the direct projection of the longwall, an approaching instantaneous steep increase of the depression curve is visible. Similarly, the decrease of the depression curve reflects that the mining is gradually terminating; this phase also depends on the distance between the actual position of the coal face and the surveying point.

During this analysis it was also verified that the development of subsidence on the undermined area corresponds to the theoretical subsidence curve and surface theory of full effective area (Neset, 1984). The results of the analysis confirmed that a large part of the total subsidence and surface deformation caused by undermining occurs during the first few months of the beginning of influence. A subsequent subsidence desisting phase, which is characterised by the gradual reduction of the dips, may reach to the order of several years, depending on the construction of the rock massif. However, it was also verified that the behaviour of the surface points depends not only on the current distance from the working face and the progress of the exploitation, respectively, but also on the geo-tectonic conditions in the locality.

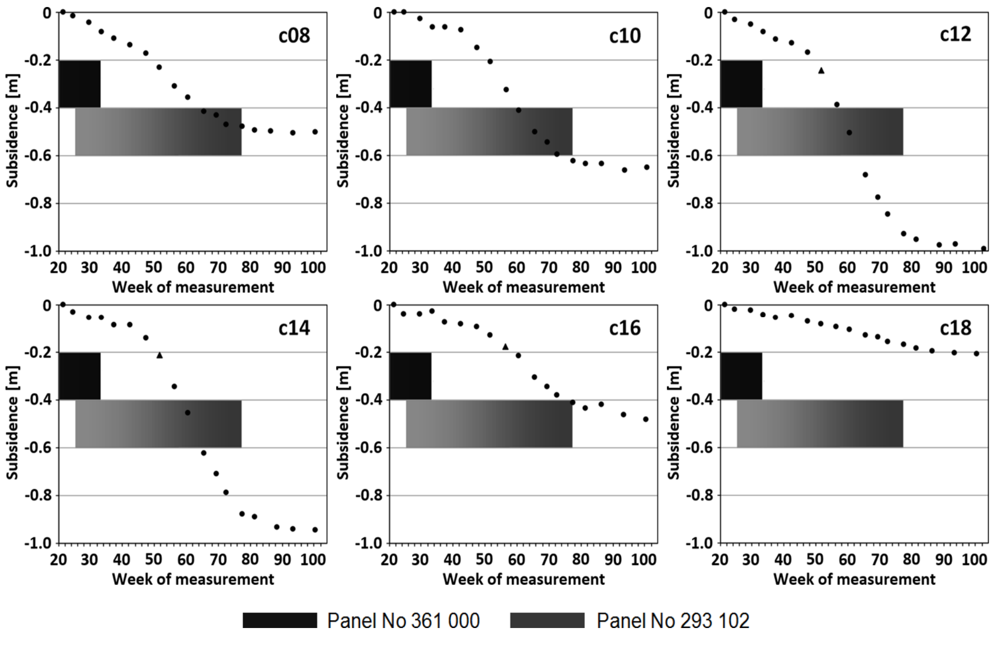

Figure 6. Temporal development of subsidence on GPS surveying points during the selected time interval

4.3. Line profiles assessment

Many of the stabilised points are part of the line profiles, which enable understanding of the development of points decrease in different directions. Results of the analysis of individual profiles show that the subsidence along the profiles located parallel with the course of tectonic faults develop regularly and almost smoothly, in accordance with the subsidence depression creation theory. In the case of the profiles which cross these tectonic lines, the development of subsidence is usually different, irregular and very complicated.

Profile C, situated along road No.475, can serve as a demonstration. The development of subsidence is complicated by surface intersecting longwalls and the tectonic faults aforementioned. The road had been repeatedly renovated due to the occurrence of expressive cracks, and sometimes crash-barriers were deformed. Figure 7 displays the complete series of depression measurements carried out along profile C. The course of the main tectonic faults caused irregular development of subsidence, where the difference of nearby points is very clear. The distinct plane boundary between the region of steep changes and unified development is likely determined by the tectonic fault "A".

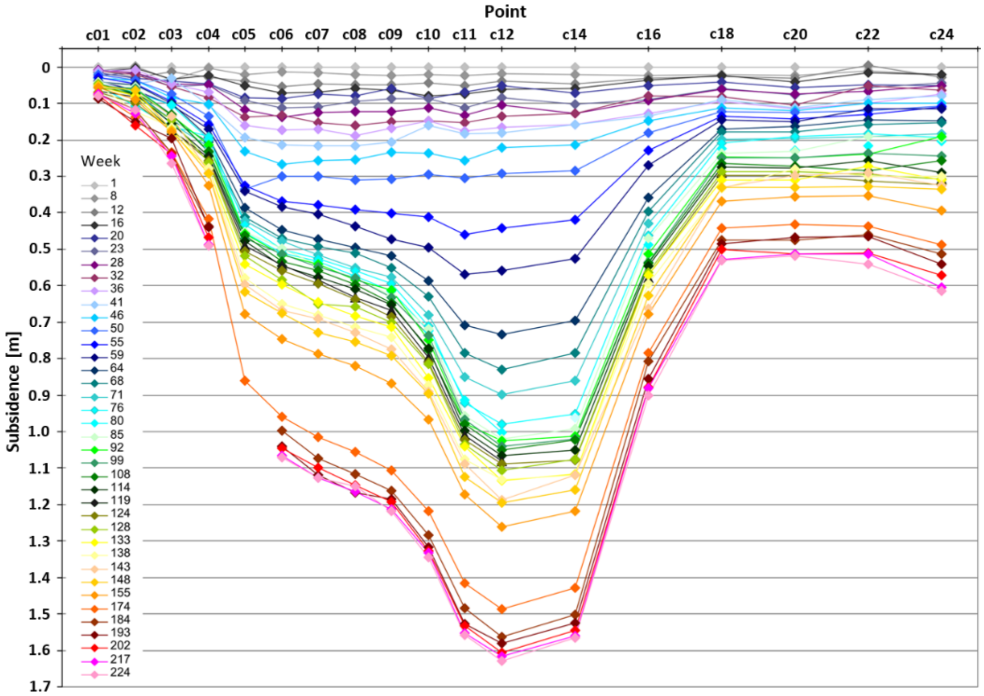

Figure 7. Development of surface subsidence along the profile C – GPS during 224 weeks of measurement

4.4. Modelling of spatio-temporal surface development

A key step in the data processing was the geo-statistical modelling of the space-temporal development of surface subsidence in the study area. The character of the GPS data enable to process such surface models. First, it was necessary to obtain spatial data about the progress of mining activities and structural-geological conditions of the selected area. These inputs were then integrated into the sophisticated processing based on mathematical statistics, geo-statistics and interpolation functions. During the process of modelling the changes in surface elevation, the corresponding interpolation from irregularly spaced points were converted into a regular grid of points. The dynamic model analysis was more complex, both in content and time, compared to the calculations reflecting only the final shape of the subsidence depression.

In the spatio-temporal modelling process, it is recommended to divide the whole evaluation period into sub-intervals and evaluate them separately. In this way a time series of grids is obtained describing the rate of surface subsidence during each of the time period. These grids serve as the basis for subsequent interpretation of empirical values. Figure 8 displays four image maps (from A to D) which correspond to measurements of surface subsidence in half-year intervals during 2007 and 2008. It should be mentioned that the credibility of the calculations depends on the density and quantity of input data. If the quantity of data increases then the results of the calculations are more precise. By gradual cumulation of these grids it is also possible to determine the development of subsidence depression during the whole study period.

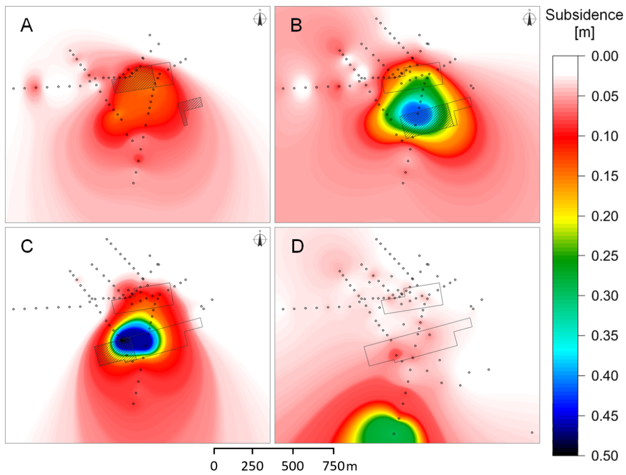

Figure 8. Spatio-temporal development of subsidence depression in monitored area within the half-year intervals: part A (January – June 2007); part B (July – December 2007); part C (January – June 2008); part D (July – December 2008)

4.5. Analysis of horizontal displacements

Unique results were obtained by performing the analysis of horizontal displacements. The advantage of GNSS techniques compared with conventional levelling was the ability to determine the motion vector within the period between two measurements. It was verified that the shape of the subsidence depression greatly depends, e.g., on the structure, geometry and tectonic distribution and faulted overburden rock mass.

Horizontal shift during the process of depression development can be defined like a change of the spatial position of a surveyed point in horizontal plane ($X - Y$). The analysis of horizontal displacements provided a detailed overview of the changes in the horizontal component of the spatial position of the surveyed points in relation to different stages of exploitation. It was possible to determine the direction of trends and shift dynamics of points in time. Besides the range and affection intensity of mining influences, the impacts of disturbance sources could be found out. The size of horizontal displacements due to undermining were compared with the occurrence of much higher subsidence. Even so, their determination effectively complements the findings on surface movements and deformations in the region of interest. Based on the graphical expression of the size and direction of the horizontal vector component of the individual points, ranges of influence of the surface due to monitored coalfaces and also the surrounding mining were determined.

The centre of gravity changes its position depending on the coal face advance. In Figure 9, the shift of point c11 represents monthly development shifts using interpolation of the monthly GPS measurements.

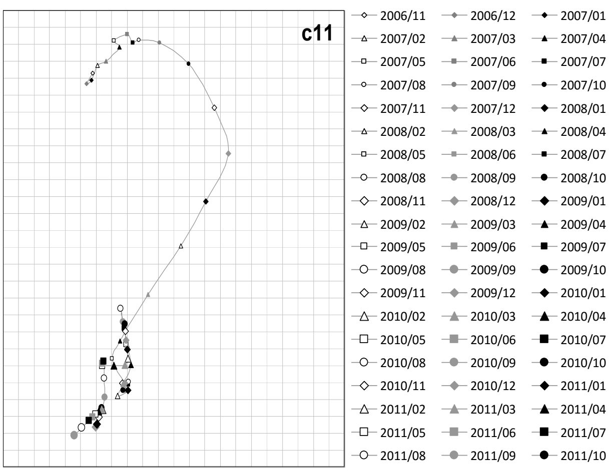

Figure 9. An example of the horizontal shifts of the point c11 (above 0.01 m square grid) (Doležalová, Kajzar, Souček, & Staš, 2012)

Furthermore, the interface has been determined as an interface of partial mining influences due to the occurrence of tectonic structures. The results of the analysis of horizontal displacements of all points in the area confirmed the obvious influence by major tectonic faults. Horizontal displacements of individual points correspond to the expected movement in the context of position points within the observation network towards exploited coalfaces. Regardless, on detailed inspection it was possible to locate the sub-regions, in which the points acted out partially or fully against expectation. It can be concluded that major tectonic faults there create a natural barrier in the massif. It is also possible to consider that the surveyed area are not separated from other mine workings around; as was assumed, the surface in the studied area could be influenced by mining in neighbouring longwalls at greater distances. This is probably one of the reasons, why subsidence values of some points are less or more deviated.

On the basis of the summary results of the realised processing, analysis and modelling demonstrates the actual development of the subsidence depression and the land relief during the whole period, respectively. These findings can be used for comparison with the original predictions of the effects of mining. Based on these data, it is also possible to predict further development of subsidence in the study area.

5. SEISMIC MONITORING

The seismic activity in mines on the territory of the eastern part of the OKCB is monitored by four various seismic and seismoacoustic systems (Holub, Holečko, Rušajová, & Dombková, 2012). The objective of these continuous observations is to ensure detached information related to the development of seismic activity during the coal exploitation as in individual longwalls, mining blocks or as in the entire OKCB. Within this detached information the considered results of the interpretation of recorded instrumental data, essentially differs from macroseismic observations. This data includes: origin time of the respective event, determination of the spatial coordinates of the focus, energetic classification of individual seismic events, frequency-energy distribution, time-dependent release of seismic energy (Benioff graph), implementation rules in the rockburst preventive scheme and limitation of areas with increasing accumulation of foci events etc.

Acoustic system (SA) is usually operated in the mined longwalls, i.e. in the immediate neighbourhood of the SA impulse sources occurring during coal exploitation (up to several hundreds of metres). Seismo-acoustic monitoring in endangered longwalls is not only important, but also obligatory from the view-point of the endangerment expected from rockbursts occurrence evaluated on the basis of regional prognosis. Reasonable spatial deployment of five SA sensors around the active longwalls enables calculation of the position and origin time of individual SA impulses, which is aimed at graphical display of their location plots and their space cumulation around the working face, and at the estimation of endangerment in the appropriate longwall.

Surface seismic network is used for investigation of rockbursts and particularly mining shock effects to surface structures and dwelling houses, a new monitoring system, including a more sophisticated approach was put into operation. These stations are distributed in whole area of the OKCB, where the mining shocks occur more frequently.

Seismic regional network was purchased and established in 1987 – 1991. This monitoring array was formerly denoted as regional diagnostic polygon consists of seven surface stations and three stations installed underground. While the surface stations are situated in shallow boreholes ($h \approx 30$ m), the seismometers of underground stations are fixed at concrete blocks. For data transmission to the central operational laboratory, telemetry is also used.

The triaxial seismometers WDS-202 ($f_0 = 2$ Hz) work within the frequency range of 2-32 Hz and complete device was considered for recording of local induced and natural origin seismic events. As shown in Figure 10 there are displayed positions of all seismic stations which belong to the regional network, moreover boundaries between basins and individual mines are in map depicted as well. The attention should be paid to 5 underground stations, because the measuring system includes only 10 channels, therefore we can apply only trios of underground stations in combination with seven stations situated in boreholes, which was applied, e.g., by Holub & Petroš (2008) and Holub, Rušajová, & Holečko (2011).

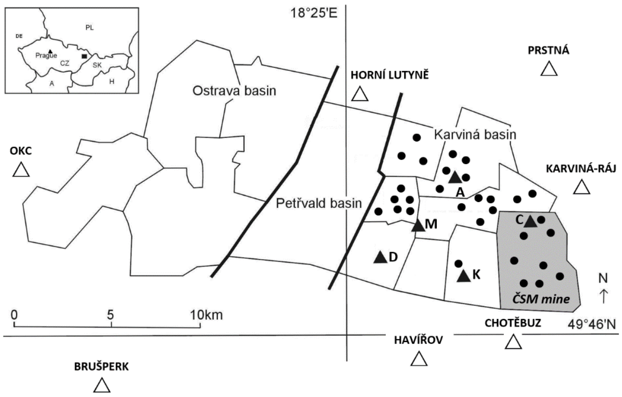

Figure 10. The layout of seismic stations within the regional network: Δ – stations situated on the surface; ▲ – stations situated underground and distribution of the seismic stations within the local seismological network ●

During the preparation of the algorithm were the time relations strictly separated from spatial ones, what enables to determine some sources of errors in localisations. As the base of time relations is the origin time (t_0) of seismic event which is calculated for every channel according to Equation 1:

$$t_0 = \frac{\left(v_p t_s - v_s t_p\right)}{\left(v_p - v_s\right)} . \qquad (1)$$

Provided that the origin time t_0 is known, then we can adjoin to all interpreted waves the relevant velocity and hypocentral distance. After the localization for every wave error in distance can be calculated by using the Equation 2:

$$\Delta r = r - v\left(t - t_0\right) . \qquad (2)$$

These errors as well as the errors in distance determination create distribution of individual values with expressive maxima. Those waves errors of which differentiate more than value of 2σ from the mode of dataset are deleted and then a new localization process continues. This iteration had to be stopped when σ is less than 250 m. If the mode of dataset varies around 0, then focus originated in the plane of coal seams, if it is considerably negative then focus was generated in upper roof above the seam. Finally, if the mode is markedly positive, then determination of t_0 was not defined correctly. Using this procedure the relevant focus is in plan obtained as the intersection of circles the radii of which are defined by Equation 3:

$$r = \left(t_p - t_0\right) \text{ and } r = \left(v_s - t_0\right) , \qquad (3)$$

for P-waves, resp. S-waves.

After the localization of the respective seismic event, seismic energy is calculated in accordance with the Equation 4 applying the measured maximal particle velocities of *S*-waves in $m.s^{-1}$. Then follows recalculation to arbitrary unit for distance at 1 km from the focus:

$$E\left(J\right) = K_E \cdot A^2 \cdot d^2 , \qquad (4)$$

where:

K_E – constant of S-wave for energy, $kg/m^{-2} \cdot s^{-1}$ (for OKCB $K_E = 8.734 \cdot 10^{12}$);

d – hypocentral distance (focus – seismic station), m;

A – maximum particle velocity $m \cdot s^{-1}$ recalculated to arbitrary unit for distance at 1 km from the focus.

For displaying the value of energy, determined as an average from all stations is possible to correct manually, i.e. to eliminate maximum and minimum value and then is defined the final value so called "accepted energy", which is given, e.g., in seismic bulletins of Green Gas DPB, Ltd.

Regional network beside the quantification of events using the determination of released seismic energy as E (J) classified individual events according to unit of magnitude M the calculation of which is based on the Equation 5:

$$M = K_M \cdot \log\left(A\right) , \qquad (5)$$

where:

K_M – constant for magnitude calculated from S-waves (for OKCB $K_M = 5.202$);

A – maximum particle velocity, $m \cdot s^{-1}$.

Local underground network is equipped only with vertical seismometers, which create an independent network distributed inside the respective mine. All seismometers use telemetry to subsequently transmit data to the central operational laboratory. The gradual development of this network is described in detail in Holub, Holecko, Rušajová, & Dombkova (2012). Present state of the distribution of all seismic stations operating inside the whole Karviná coal mine district is presented in Figure 10. The concept of instrumentation is based on conditions of intrinsically safety related to operation in gassy mines. Nevertheless, this local establishment is operated mainly for purposes of geomechanical service, while regional network is mostly used for scientific and technological purposes.

Principles of foci localization are identical with the approaches applied for regional network.

The estimation of the energy of mining-induced seismic events, recorded automatically at seismic stations within the territory of coal mines, is based on the assumption that the energy is proportional to the square limited by the function $f = v^2(t)$ within the interval (0; T), and thus the following Equation 6 has been adopted for energy calculation:

$$E\left(J\right) = K \int_0^T u^2 dt , \qquad (6)$$

where:

K – constant defined characteristics of transmission conditions;

T – the time interval from the viewpoint to signal duration (for OKCB $T = 1.5$ s).

During the comprehensive processing, the seismic energy is calculated after localizing the focus of the event for every station separately, but the resulting value is obtained as the modus of values excluding the minimum and maximum values of the whole dataset.

In considered time the local seismological network in the CSM mine consists of eight underground stations. Three of them (No.851, 861 and 881) were located in mining blocks No.0 and 1 (Fig. 2), where the foci of five seismic events were detected. The flow chart of mining in this area is displayed in Figure 11, where individual stages of mining are depicted by rectangles situated in upper part of this graph.

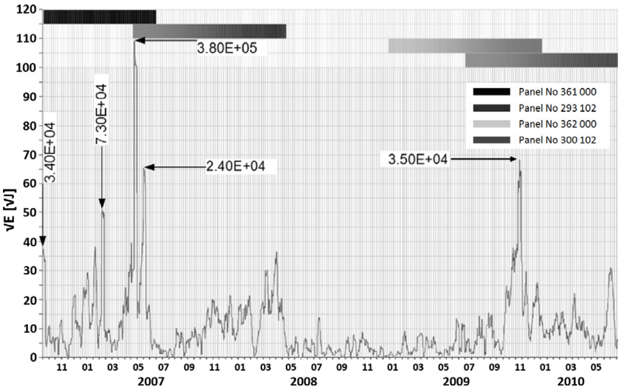

Figure 11. Running graph of Benioff derivative S from October 2006 to June 2010, including five identified moderate seismic events recorded within the time interval of experimental observations

In Table 1, origin times, foci coordinates, magnitude and values of released seismic energy are given. In the column denoted as "remarks" BTPVR indicates realisation of the blasting operation performed in the main roof of longwall No.300100, having a total charge of 2.264 kg of explosives. Further "SA data" indicate seismoacoustic event, and arrival time which was picked up on records.

Data gathered within the process of observation and the final results of localisation are stored in the database of the operational data centre of Green Gas DPB Ltd., Paskov. This robust database was used as soon as various approaches to the display of observed and calculated data was needed for detailed seismological analysis. The essential data was applicable for construction, e.g., of the stepwise summation of the Benioff graph, location plots for the predetermined area and energy-frequency distribution. The Benioff diagram practically illustrates the gradual accumulation of relative deformations in the form of stepwise curves defined as $\sum\sqrt{E}$ (J) for a given time unit. The release of seismic energy in time generally reflects the instantaneous response of the massif to its stress-strain state. Radiated seismic energy is a parameter of decisive importance applied for the quantitative assessment of classifications of particular seismic events.

Based on long-term seismological observations in the OKCB, the practical application of parameter S ($\sqrt{E}$/day) (√J/t), which represents the derivative of the Benioff diagram was implemented into the system of rockbursts preventative regime (Vajter, Knotek, & Holub, 1989; Holub, Vajter, Knotek, & Trávníček, 1991).

Table 1. Seismic events with energy $E \geq 10^4$ J recorded within the time interval 10/2006 – 6/2010 in the investigated area

Date	Time	*X*	*Y*	*Z*	Magnitude	Energy, J	Remarks
01.10.2006	14:06:37.420	1104278	451403	–664	1.17	3.40E + 04	BTPVR 2264 kg R300100 SE6
18.02.2007	02:02:16.030	1103796	450903	–649	1.34	7.30E + 04	CSM:SA R361000
07.05.2007	02:04:12.790	1103808	450903	–616	1.72	3.80E + 05	CSM:SA R361000
29.50.2007	15:19:03.470	1103805	450825	–655	1.18	2.40E + 04	CSM:SA R361000
03.11.2009	00:19:53.910	1105093	450957	–544	1.34	3.50E + 04	Mine shock; CSM:SA R331202

Source: Green Gas DPB bulletins, 2018

The value S is defined as a moving weekly average of the Benioff graph increment using Equation 7, where $n = 7$ days. The crucial problem is derivation of the limited safe value of S for a given longwall because in exceeding the limited value increasing endangerment can be expected:

$$S = \frac{\sum_{i=1}^{n}\sqrt{E_i}}{n}. \quad (7)$$

Comparing the Benioff graph and the graph of its derivative, the latter has the advantage of highlighting the arrival of a stronger phase appearance. Displayed successively in Figure 11 are five seismic events, the first event in the initial part of the graph corresponds to the blasting operation. All events coincided with the period of coal extraction in longwalls No.361000 and 293102 as seen in Figure 11. This was followed by a period of eight months mining interruption with very low seismic activity, which slightly increased when longwall No.300102 was put into operation. Since January 2009, longwall No.362000 was opened, and at the beginning of November 2009 one event was detected as having released energy in the order $E \approx 1.10^4$ J. As for the level of seismic activity, it was confirmed that the level inside the area of interest was relatively very low, especially within the time interval when mining was stopped for almost eight months. Finally, it was concluded that no pronounced seismic manifestations in the course of geodetic observations were found out.

6. CONCLUSIONS

The results of the assessment and analyses of spatial data demonstrate the real development of the subsidence depression under study and the relief changes of the landscape during the investigated period, respectively. Based on these results it is possible to perform a comparison of current dimensions with the original rate of affection.

Dynamics of surface changes in progress are closely associated with actual coal extraction. It was documented that development of subsidence on the undermined region correspond with the theoretical subsidence curve.

Most of the subsidence and surface deformations caused by undermining are expected during several subsequent months. Afterwards, a phase of subsidence decay is expected to occur, which will be characterised by sudden decrease of the subsidence rate, which could take several years.

From the obtained spatial data it is also possible to evaluate horizontal movements, and on the basis of these, to determine the direction by which the surface is influenced from and to define the appropriate boundary of the impact of different influences induced by mining.

Based on the analysis of available seismic data and surface GPS measurements, it has been documented that during the investigated period any expressive influence by the development of displacements and deformations of the surface due to seismic activity was not observed. Therefore, it can be concluded that at similar low seismic activity the appropriate impact of seismic event occurrence may be neglected.

It was recognised that all methods applied in this study represent very helpful tools for surveying subsidence depression and simultaneous monitoring of seismic activity development on an undermined area.

ACKNOWLEDGEMENTS

This article was written in connection with the Project Institute of Clean Technologies for Mining and Utilization of Raw Materials for Energy Use – Sustainability Program (reg. No.CZ.1.05/2.1.00/03.0082 and MSMT LO1406), which is supported by the Research and Development for Innovations Operational Programme financed by the Structural Funds of the European Union and the Czech Republic project for the longterm conceptual development of research organisations (RVO: 68145535).

Many thanks to Dr. Karel Holub, emeritus researcher from the Institute of Geonics of the Czech Academy of Sciences, for his helpful comments and advices during preparation of manuscript. R.I.P.

REFERENCES

Bell, F.G., Stacey, T.R., & Genske, D.D. (2000). Mining Subsidence and Its Effect on the Environment: Some Differing Examples. *Environmental Geology*, *40*(1-2), 135-152. https://doi.org/10.1007/s002540000140

Bell, F.G., & Donelly, L.J. (2006). *Mining and Its Impact on the Environment*. London: CRC Press, Taylor & Francis Group. https://doi.org/10.4324/9780203969519

Bláha, P., Doležalová, H., Müller, K., & Skopal, R. (2006). Observations on Heights on the Margin of Subsidence Depression. *Transactions of the VŠB Technical University of Ostrava, Civil Engineering Series, 2*(IV), 9-15.

Blodgett, S., & Kuipers, J.R. (2002). *Technical Report on Underground Hard-Rock Mining: Subsidence and Hydrologic Environmental Impacts*. Bozeman, Montana, United States: Center for Science in Public Participation.

Bogusz, M., & Mendecki, M. (2011). Seismic and Geodetic Observations of Subsidence Trough Development Over a Longwall Face in a Coal Bed under Extraction. *Geoplanet: Earth and Planetary Sciences*, 71-79. https://doi.org/10.1007/978-3-642-19097-1_7

Crane, W.R. (1931). *Factors Influencing Subsidence and Ground Movement*. Washington, United States: U.S. Bureau of Mines, Information Circular.

Doležalová, H., Holub, K., & Kaláb, Z. (2008). Underground Coal Mining in the Karviná Region and Its Impact on the Human Environment (Czech Republic). *Moravian Geographical Reports*, *16*(2), 14-24.

Doležalová, H., Kajzar, V., Souček, K., & Staš, L. (2012). Analysis of Surface Movements from Undermining Time. *Acta Geodynamica et Geomaterialia*, *9*(3), 358-400.

Dulias, R. (2003). Subsidence Depressions in the Upper Silesian Coal Basin. *Geomorphic Transactions*, (2), 11-16.

Geertsma, J. (1973). Land Subsidence Above Compacting Oil and Gas Reservoirs. *Petroleum Technology Journal*, *25*(06), 734-744. https://doi.org/10.2118/3730-pa

Gisotti, G. (1991). A Case of Induced Subsidence for Extraction of Salt by Hydrosolution. Land Subsidence. In *Proceeding 4th International Symposium on Land Subsidence* (pp. 235-238). Houston, Texas, United States: International Association of Hydrological Sciences.

Green Gas DPB bulletins. (2018). Retrieved from http://www.dpb.cz/geofyzika

Holub, K., Vajter, Z., Knotek, S., & Trávníček, L. (1991). Application of Results of Seismologic Monitoring During the Operation in Mine Workings in the Ostrava-Karviná Coal Basin. *Publications of the Institute of Geophysics, Polish Academy of Sciences*, *M-15*(235), 219-228.

Holub, K., & Petroš, V. (2008). Some Parameters of Rockbursts Derived from Underground Seismological Measurements. *Tectonophysics*, *456*(1-2), 67-73. https://doi.org/10.1016/j.tecto.2006.12.013

Holub, K., Rušajová, J., & Holečko, J. (2011). Particle Velocity Generated by Rockburst During Exploitation of the Longwall and its Impact on the Workings. *International Journal of Rock Mechanics and Mining Sciences*, *48*(6), 942-949. https://doi.org/10.1016/j.ijrmms.2011.05.004

Holub, K., Holecko, J., Rušajová, J., & Dombkova, A. (2012). Long-Term Development of Seismic Monitoring Networks in the Ostrava-Karviná Coal Mine District. *Acta Geodynamica et Geomaterialia*, *9*(2), 115-132.

Holzer, T.L. (1984). Ground Failure Induced by Ground-Water Withdrawal from Unconsolidated Sediment. *Man-Induced Land Subsidence. Geological Society of America Reviews in Engineering Geology*, (6), 67-106. https://doi.org/10.1130/reg6-p67

Hyndman, D., & Hyndman, D. (2011). *Natural Hazards and Disasters*. Belmont, United States: Cengage Learning.

Idziak, A.F., & Dubiel, R. (2011). *Geophysics in Mining and Environmental Protection*. New York, United States: Geoplanet: Earth and Planetary Sciences. https://doi.org/10.1007/978-3-642-19097-1

Jiránková, E., Staš, L., Kajzar, V., & Doležalová, H. (2013). Mechanism of Rigid Overlaying of Carboniferous Strata Failure in Face Mining in the Case of Multiseams Deposit. *Acta Geodynamica et Geomaterialia*, *10*(2), 189-195.

Kajzar, V., Doležalová, H., Staš, L., & Souček, K. (2009). Analysis of Horizontal Movements Accompanying Development of Subsidence Depression in Non-Trivial Geo-Mechanical Conditions. In *Proceeding 9th International Multidisciplinary Scientific GeoConference* (pp. 735-739). Sofia, Bulgaria: Curran Associates.

Kajzar, V. (2011). *Modelling the Effects of Mining of Mineral Deposits*. Ph.D. Ostrava, Czech Republic: VŠB Technical University Ostrava.

Knothe, S. (1953). The Influence of Time to Creation a Sedimentation Basin. *Archivum of Mining and Metallurgy*, *1*(1).

Kuenzer, C., Zhang, J., Tetzlaff, A., van Dijk, P., Voigt, S., Mehl, H., & Wagner, W. (2007). Uncontrolled Coal Fires and Their Environmental Impacts: Investigating Two Arid Mining Regions in North-Central China. *Applied Geography*, *27*(1), 42-62. https://doi.org/10.1016/j.apgeog.2006.09.007

Leica. (2018). *Leica GPS1200 Series Technical Data*. [online]. Available at: http://www.gefos-leica.cz/public/img/produkty/geodeticke-pristroje/smartrover/leica_gps1200_technicalda-ta_en.pdf

Neset, K. (1984). *The Influences of Undermining (Mining Surveying IV)*. Praha: SNTL.

Schenk, J. (2005). *Measurement of Motions and Deformations in the Subsidence Depression*. Ostrava, Czech Republic: VŠB Technical University Ostrava.

Stracher, G.B. (2007). Geology of Coal Fires. Case Studies from Around the World. *Reviews in Engineering Geology*, (XVIII), 283.

Vajter, Z., Knotek, S., & Holub, K. (1989). Application of Seismological Observations in Geomechanical Practice. *Acta Montana*, (81), 115-126.

Whittaker, B.N., & Reddish, D.J. (1989). *Subsidence: Occurrence, Prediction and Control.* Amsterdam, Netherlands: Elsevier.

Yarbrough, R.E. (1983). *Surface Mining Environmental Monitoring and Reclamation*. New York, United States: Elsevier.

ГЕОДЕЗИЧНІ ТА СЕЙСМОЛОГІЧНІ СПОСТЕРЕЖЕННЯ ДЛЯ ВИВЧЕННЯ УТВОРЕННЯ ПРОСІДАНЬ НА ШАХТІ CSM (ЧЕСЬКА РЕСПУБЛІКА)

В. Кайзар

Мета. Дослідження причин утворення просідань земної поверхні в околиці шахти CSM (Чеська Республіка) за допомогою геодезичних і сейсмологічних методів спостереження.

Методика. В роботі використано сейсмічні методи для визначення локалізації місць явищ техногенної сейсмічності, їх класифікації за магнітудами і кількістю виділеної сейсмічної енергії та її частотного розподілу; побудову графіка Беньофа та його модифікацію для оцінки безпеки суміжних до шахти територій; моделювання просторово-часового розвитку опускання поверхні за допомогою GPS-вимірювань.

Результати. У результаті оцінки та аналізу просторових даних була визначена реальна область просідань і зміни навколишнього рельєфу протягом всього часу проведення досліджень. Ґрунтуючись на аналізі наявних сейсмічних даних та наземних GPS-вимірювань, встановлено, що протягом досліджуваного періоду ніякого виразного впливу розвитку зсувів і деформацій поверхні через сейсмічну активність не спостерігалося. Виконано моделювання просторово-часового розвитку опускання поверхні у досліджуваній області, що дозволило визначити швидкість осідання поверхні з часом. Визначено горизонтальні переміщення окремих точок і встановлено, що великі тектонічні розломи створюють природний бар'єр зсувам у масиві.

Наукова новизна. Використання унікального комплексу методів дослідження та моніторингу, застосовані у даній роботі, дозволили точно виявити область просідання поверхні й причини її утворення, а також здійснити моніторинг сейсмічної активності в районі, порушеному гірничими роботами.

Практична значимість. Отримані результати дозволяють порівняти сучасний стан утворених просідань з їх початковими параметрами, а також прогнозувати інтенсивність їх розвитку у часі.

Ключові слова: *Остравсько-Карвинський вугільний басейн, величина просідання, методи геодезичної розвідки, сейсмічний моніторинг, переміщення*

ГЕОДЕЗИЧЕСКИЕ И СЕЙСМОЛОГИЧЕСКИЕ НАБЛЮДЕНИЯ ДЛЯ ИЗУЧЕНИЯ ОБРАЗОВАНИЯ ПРОСЕДАНИЙ НА ШАХТЕ CSM (ЧЕШСКАЯ РЕСПУБЛИКА)

В. Кайзар

Цель. Исследование причин образования проседания земной поверхности в окрестности шахты CSM (Чешская Республика) при помощи геодезических и сейсмологических методов наблюдения.

Методика. В работе использовано сейсмические методы для определения локализации очагов явлений техногенной сейсмичности, их классификации по магнитудам и количеству выделенной сейсмической энергии и ее частотного распределения; построение графика Беньофа и его модификацию для оценки безопасности прилегающих к шахте территорий; моделирование пространственно-временного развития опускания поверхности при помощи GPS-измерений.

Результаты. В результате оценки и анализа пространственных данных была определена реальная область проседаний и изменения окружающего рельефа в течение всего времени проведения исследований. Основываясь на анализе имеющихся сейсмических данных и наземных GPS-измерений, установлено, что в течение исследуемого периода никакого выразительного влияния развития смещений и деформаций поверхности из-за сейсмической активности не наблюдалось. Выполнено моделирование пространственно-временного развития опускания поверхности в исследуемой области, позволившее определить скорость оседания поверхности с течением времени. Определены горизонтальные перемещения отдельных точек и установлено, что крупные тектонические разломы создают естественный барьер смещениям в массиве.

Научная новизна. Использование уникального комплекса методов исследования и мониторинга, примененные в данной работе, позволили точно выявить область проседания поверхности и причины ее образования, а также осуществить мониторинг сейсмической активности в районе, затронутом горными работами.

Практическая значимость. Полученные результаты позволяют сравнить современное состояние образовавшейся впадины с ее первоначальными параметрами, а также прогнозировать интенсивность ее развития со временем.

Ключевые слова: *Остравско-Карвинский угольный бассейн, величина проседания, методы геодезической разведки, сейсмический мониторинг, перемещения*

ARTICLE INFO

Received: 26 December 2017
Accepted: 16 March 2018
Available online: 23 March 2018

ABOUT AUTHORS

Vlastimil Kajzar, Doctor of Philosophy, Junior Researcher of the Department of Geomechanics and Mining Research, Institute of Geonics of the Czech Academy of Sciences, 1768 Studentska St, 70800, Ostrava, Czech Republic. E-mail: vlastimil.kajzar@ugn.cas.cz