MONITORING AND ANALYSIS OF SURFACE CHANGES FROM UNDERMINING

MONITORING A ANALÝZA POVRCHOVÝCH PROJEVŮ PODDOLOVÁNÍ

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Abstract

It is well known that the exploitation of mineral deposits negatively affects the environment. In the case of underground mining, there are usually the most serious effects which are associated with mining activities: movements and surface deformations lead to the creation of subsidence depressions.

The determination of the actual state of surface changes by conventional surveying methods is technically exacting, time-consuming and very expensive. With the development of geo-information technologies, new approaches arise and they can be applied to resolving this issue. These resources seem to be suitable not only for providing the necessary spatial information on ongoing processes, but also for their subsequent processing and comprehensive evaluation.

The presented paper deals with the possibilities of applying geo-information technologies for monitoring and evaluating the effects of underground mining on surface, summarizes the actual state of this research at ICT, and offers alternatives for their use in the future.

Abstrakt

Je známo, že exploatace ložisek nerostných surovin negativně ovlivňuje životní prostředí. V případě hlubinného dobývání jsou bezpochyby nejzávažnějšími důsledky spojenými s těžbou pohyby a deformace povrchu vedoucí k vytvoření poklesové kotliny.

Stanovení skutečného stavu povrchových změn je konvenčními měřickými metodami technicky, časově i finančně velmi náročné. S rozvojem geoinformačních technologií dnes přicházejí nové přístupy, jež mohou být aplikovány při řešení této problematiky. Tyto prostředky se zdají být vhodné nejen k zajišťování potřebných prostorových informací o probíhajících procesech, ale rovněž k jejich následnému komplexnímu zpracování a vyhodnocení.

Předkládaný příspěvek se věnuje možnostem uplatnění geoinformačních technologií pro sledování a hodnocení vlivů hlubinného dobývání na povrch. V jeho rámci jsou shrnuty poznatky zjištěné dosavadním výzkumem a nabízeny alternativy jejich využití do budoucna.

Key words: mining effects, subsidence depression, surveying and monitoring methods, GNSS, spatio-temporal data analysis

1 INTRODUCTION

The underground mining of raw material deposits leads to the formation of vacant underground spaces. The spaces are then filled with the mass of overlying strata which bend into them and break through. In the case of the extraction of a large deposit, the ongoing displacements of materials show up on the surface, typically by creating a subsidence depression (a basin). Movements and deformations occurring during its formation negatively affect both the surface and the objects associated with it. Although the theory for the assessment and prediction of the surface movements and deformations above the exploited deposits have been systematically developed for more than a century, it is not yet possible to perfectly describe the expected surface changes with certainty.

At present, the extent of the affected surface is numerically determined mainly by relatively simple prediction models based on generally accepted theories. The data obtained by seldom observations *in situ* are only used for local validation of predictive calculations. However, the real state of the surface changes is not always entirely consistent with the predictions. Therefore, there is a need to design a new universally applicable method for detecting surface changes in undermined areas to complement and/or replace the existing survey methods used so far.

On an example of newly forming subsidence depressions, our effort is to demonstrate the possibilities of using modern geo-information technologies for capturing real spatio-temporal surface changes associated with the creation of subsidence depressions. It is based on a combination of direct and indirect surveying techniques, particularly the methods using global positioning navigation systems, supplemented by other geodetic and geophysical techniques and remote sensing. The collected data are then evaluated in the context of geological and geomechanical situation, advance of longwall mining and predicted surface changes.

2 AREAS OF INTEREST

The proposed procedures were subsequently applied to the selected pair of active mining areas. Both localities are situated in the Upper Silesian Coal Basin near the town of Karviná in the north-eastern part of the Czech Republic which has a long history of the hard coal deposits mining.

The rock mass consists of typical for the Upper Silesian Coal Basin upper carboniferous molasse sediments consisting mostly of coal-bearing siliciclastic continental deposits. The Upper Silesian Coal Basin is divided into tectonic blocks by a set of normal faults of tens to hundreds of meters amplitude (Dopita, 1997). The longwall method with controlled caving was used as the mining method.

The local environment can be characterized as a mining landscape with no permanent buildings. Vegetation begins to flourish on the former mine spoil deposits. The effects of undermining may cause significant changes mainly in local roads and rail tracks, infrastructure projects, or in the stability of sewage storage basin dams (Kajzar et al. 2012). The surface manifestations of mining do not include only surface movements and deformations, but also the manifestations caused by mining reclamation, i.e. creating mine spoil deposits on the surface, flooding parts of the affected surface, etc.

2.1 Louky locality

The first locality, called Louky, is situated in the mining area of the ČSM colliery. The selected northern part of this locality occupies an area of c. 6 km^2. The rock massif of this area belongs to the 0 and 1 mining blocks and was exploited in the past. Due to the significant tectonic faults in the massif, the coal seams were mined in an insular way. The first exploitation started in 1991. In the following years, there were several horizontal mining panels exploited. The new exploitation period started in 2006. In this period (until 2012), there were four horizontal coal mining panels gradually exploited at the depth of around 1000 m under the surface. The average exploited thickness of the mining panels varied from 2.0 to 3.6 m. For the detail information please see Tab. 1.

Tab. 1 Mining panels data

Mining panel	a	b	c	d
Start of exploitation	10/2006	05/2007	01/2009	07/2009
End of exploitation	06/2007	04/2008	12/2009	06/2010
Face length	180 m	190 m	160 m	180 m
Lateral length of longwall advance	480 m	880 m	600 m	670 m
Depth under the surface	945 m	995 m	960 m	1025 m
Average exploited thickness	2.0 m	3.6 m	2.4 m	2.5 m
Mining panel area	78.600 m^2	152.600 m^2	87.000 m^2	99.000 m^2

Source: OKD, a.s.

2.2 Gabriela locality

The second one, Gabriela locality, is situated in the Darkov mining area. The locality occupies an area of c. 3 km^2. The mining history goes back to the 19th century in this locality. The tectonic faults called “Gabriela”, “Eliška” and “Ležatá” are main geological structures which substantially influence the stress state of the rock mass in this area. There also occur some tectonic faults of a minor importance in the vicinity of the exploited mining panel.

In the Gabriela locality, the exploitation of the last mining panel started in July 2011. The exploited mining panel is located east of former safety pillars of the Gabriela mine. This mining panel is situated beneath the previously extracted mining panels and its exploited thickness is very high as for local conditions. It is situated in the coal seam No. 40 called “Prokop” that has a total thickness of about 6-7 m. The depth of the coal seam Prokop varied from c. 790 m to 820 m. The face length of the mining panel is 200 m and the lateral length of longwall advance is up to 900 m. The average thickness of extraction is 5.5 m. More than 20 coal seams were gradually exploited above the studied mining panel in the past (Kajzar et al. 2012).

3 GNSS – MAIN SURVEYING METHOD

Observation networks of fixed points were built in the selected areas to observe the process of creation of a subsidence depression above exploited coal mining panels. Building the Louky observation network with around 100 points started in 2007. Based on the gained experience, another observation network was built in the framework of ICT in the Gabriela locality in 2011. This network consists of 36 fixed points covering the whole studied area.

GNSS, specifically the GPS system, was used to record the spatial changes in the fixed points of both observation networks not only during the actual mining, but also in the periods between each longwall mining activity (in case of the Louky locality) and during the final period after the termination of all mining activities.

GNSS is a method that can be successfully used in an undermined area. Its advantage over other common geodetic methods lies not only in providing space coordinates of a surveyed point, but also in the ability of a quick connection to the stable area not affected by undermining. This ability is very important because common geodetic methods of surveying may take time to connect the large undermined area to the non-affected stable area which means that these methods are not only time consuming, but they may also bring inaccuracy to the surveying as the points in the undermined area may move meanwhile due to undermining. The ability to provide space coordinates of points is also important. As a subsidence is the main after-effect from undermining, repeated geodetic levelling is the most common way to survey the undermined areas. But it only provides the information about vertical changes of the surface points or profiles, while the information about horizontal displacements, i.e. the direction of the surface movements is absent. But GNSS provides both the information. Our previous research of the undermined areas proved that the analysis of both vertical and horizontal movements enables more complex and precise evaluation of surface changes and their causes in the rock massif (Doležalová et al. 2009, Doležalová et al. 2010, Doležalová et al. 2011, Doležalová et al. 2012, Kajzar et al. 2011, Staš et al. 2009).

For surveying in studied localities, a static way of GNSS geodetic surveying method was chosen, with the observation for at least 10 minutes on each point with the Leica GPS system 1200. While a GNSS field receiver was surveying in the observation network, a GNSS reference station was surveying on a trigonometric point situated outside the assumed undermining effects, at a distance of several kilometres from the observation network. This point belongs to the national network.

For the used GNSS equipment, the stated accuracy for static surveying with subsequent post-processing is 0.005 m + 0.5 ppm in the horizontal position of a point and 0.010 m + 0.5 ppm in the vertical position of a point. Since the surveyed points were only few kilometres far from the reference point, constellation geometry was controlled during the whole observation and precise ephemeris were input into post-processing, the obtained accuracy of the spatial position of surveyed points may be estimated within an interval from 0.01 to 0.03 m (Kajzar et al. 2012).

In order to record an incremental development of undermining effects, the interval of roughly 1 or 1.5 month was chosen for repeated GNSS surveying action at first. Afterwards, the data from field surveying were processed on a computer. The spatial coordinates of the surveyed points in the WGS-84 and S-JTSK systems are the results obtained from the post-processing by the Leica GeoOffice software application.

4 DATA EVALUATION AND ANALYSIS

The data obtained by this surveying method are used as a suitable source of input information for the analysis of surface changes in the observed areas. Thanks to the re-use of this method and also thanks to the fixation of the points of the observation network in the form of lines and scattered points, it is possible to evaluate the continuous development of the subsidence and horizontal displacements of individual points as well as over the entire observed area.

The effective work with the obtained data was allowed by modern software geo-information technologies. Where necessary, their functionality was extended with newly created specialized software tools (scripts, extensions, applications) for the new procedures of processing and evaluation. The tools then allowed performing very interesting spatial analyses with the acquired data.

4.1 Analysis of point subsidence development in time

By performing this analysis, it was verified that the development of subsidence in the undermined area corresponds to the theoretical subsidence curve and to the theory of the full effective area. It was confirmed that a large part of the total subsidence and deformations of the surface caused by undermining occur during the next few months. After that, the subsidence desisting period follows characterized by a gradual reduction in the size of subsidence which may take several years. But it was also proved that the behaviour of the surface points as a reaction to the exploitation of the mining panels depends not only on the distance of the point from the mining panel, i.e. approaching the coalface, but also on the geo-tectonic conditions in the given locality (Doležalová et al. 2009, Doležalová et al. 2012).

4.2 Evaluation of line profiles

Many of the fixed points are parts of line profiles. Thanks to them, it is possible to evaluate the development of subsidence in different directions and in the context of surrounding points at the same time.

The results of the analysis of two selected profiles in the Louky locality (Fig. 1) show that while the subsidence in the profiles that are situated in parallel (the left graph) with the tectonic faults reported almost regular and smooth development throughout their length (in accordance with the theory of the creation of a subsidence depression; Neset, 1984), in the case of profiles intersecting these tectonic faults (the right graph), the subsidence development is usually quite different, irregular and very complicated. The major tectonic fault caused an irregular course of the profile subsidence where the difference in subsidence of close points above the fault was marked (Doležalová et al. 2009).

4.3 Analysis of horizontal displacements

A horizontal movement of a surface point can be defined as a change in its position in a horizontal plane. The size of the horizontal displacement from undermining is much smaller than the subsidence. However, its diagnosis effectively complements the evaluation of movements and surface deformation processes in the area of interest. Based on graphical evaluation of horizontal displacements, we are able to define the influence of a mining activity on the resulting change in position of surveyed points.

Determining the directions of point movements is a great benefit to the evaluation of the process of subsidence depression formation. We can thus detect the interface caused by a tectonic fault or interface of the various mining effects. The results of the analysis of the horizontal displacements of all points in the Louky locality confirmed the significant influence of the major tectonic fault. The horizontal movements of individual points corresponded to the expected movements in the context of position of points in the observation network towards the exploited mining panels. However, by a close-up view, it was possible to locate subareas, in which the points behave partly or totally out of the said presumption. We may conclude that the major tectonic fault makes a natural barrier (Doležalová et al. 2010, Doležalová et al. 2012).

4.4 Analysis of the time-dependence of surface changes on the progress of exploitation

The dynamics of the development of subsidence and displacements is not uniform and it is closely linked with mining activities. The change of a spatial position is always the most marked in the period of active mining. The main reaction of surface points to the changes in the rock massif and the movements of the points were different, according to their surface position, local geo-mechanical conditions etc. (Doležalová et al. 2012).

4.5 Modelling of spatio-temporal surface development

The acquired spatial data are supplemented by knowledge of mining activity, geological conditions and structural geology in the areas. Then they are processed with sophisticated mathematical statistics, geo-statistics methods and interpolation functions. In the modeling process, the values of height changes were calculated from irregularly located points into a regular network of points (the grid) using a suitable interpolation method. In the process of spatio-temporal modeling, it was appropriate to divide the evaluation period into sub-intervals, and to process them separately. The final model is then presented by a series of created grids corresponding to the

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individual time intervals, which represents the spatio-temporal development of surface height changes in the studied area during the evaluated period.

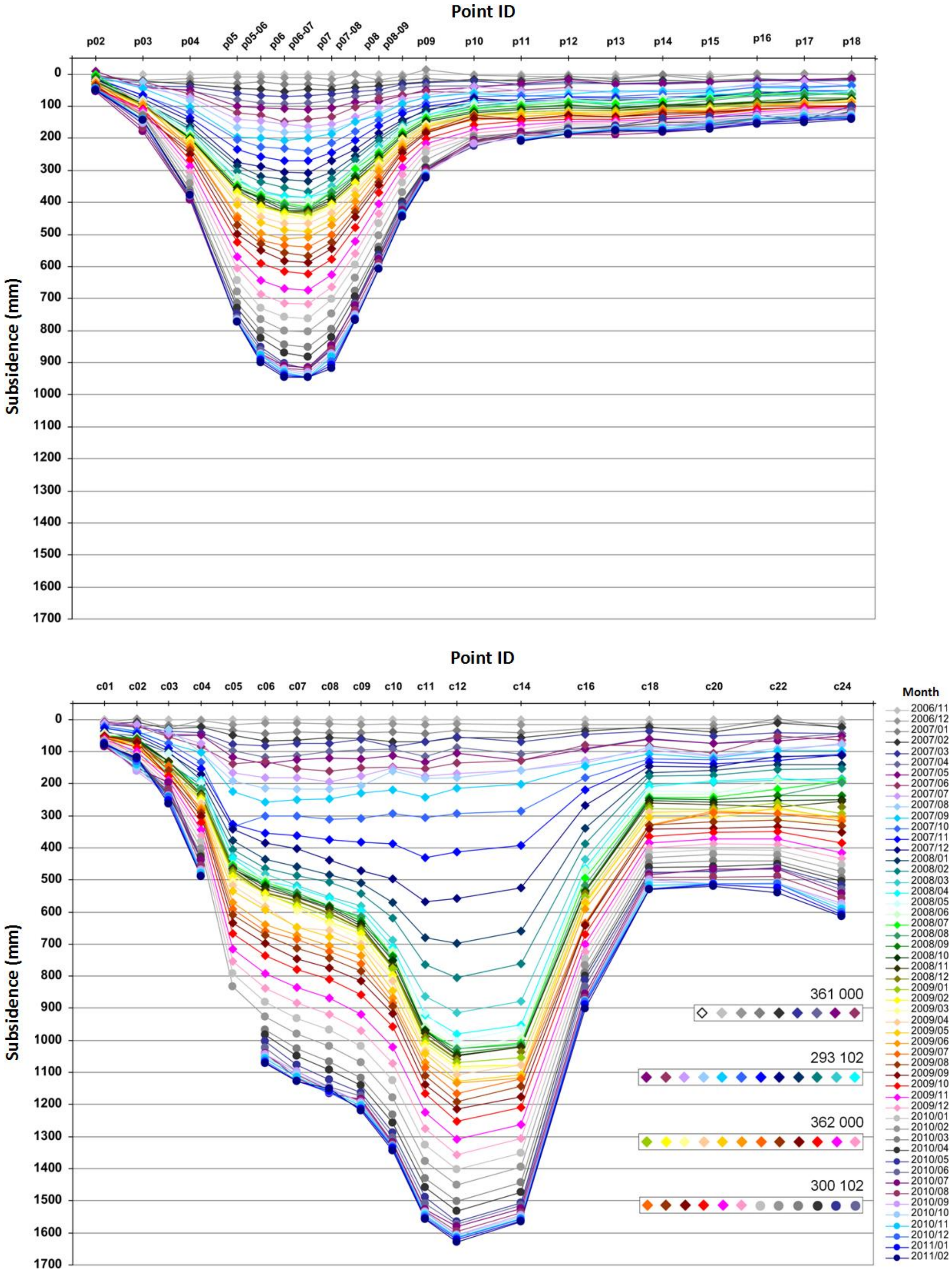

Fig. 1. Subsidence development of two selected line profiles in Louky locality. (Kajzar, 2011)

The results of comprehensive assessment are the spatio-temporal models describing the evolution of real subsidence above the exploited coal deposit which occurred in the selected area (Fig. 2). It was proved that the shape of the subsidence depression markedly depends among others on the structure, geometry of tectonic zoning and the massive failure of the overburden massif (Doležalová et al. 2010).

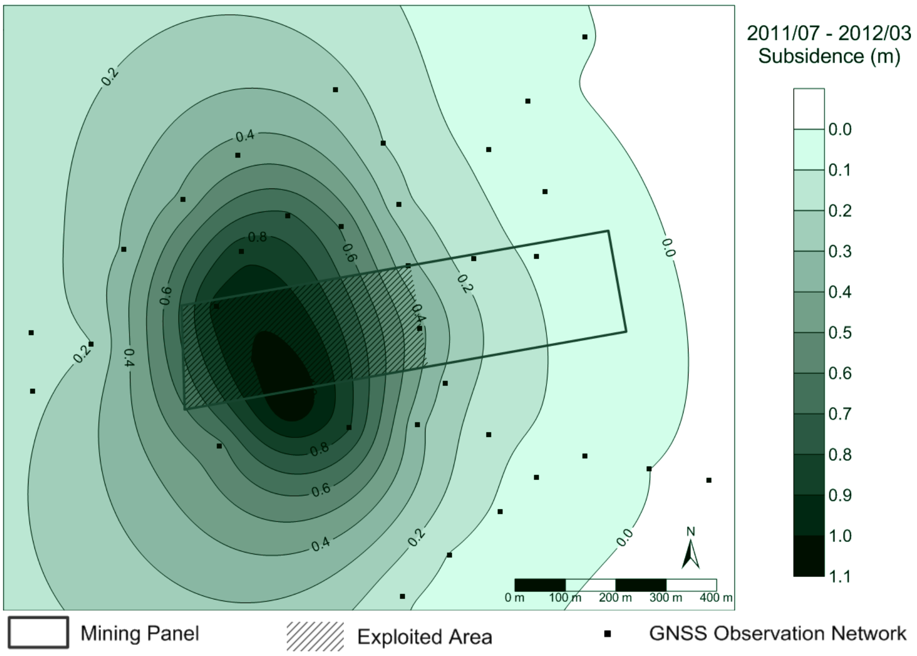

Fig. 2 Contour map of surface subsidence and mined out area of the mining panel in the Gabriela locality 8 months after the start of exploitation (Jiránková et al. 2013)

The results of processing and analysis of the obtained spatial data together with the created spatio-temporal models demonstrate the actual development of the studied subsidence depression, i.e. the landscape relief, during the observed period, which can be used to be compared with the initial predictions of the undermining influence. Based on the data, it is also possible to make a prediction of the development of the studied area in the future.

4.6 Comparison with official calculated predictions

The obtained surface changes were confronted with the results of official calculated predictions (provided by a mining company). Thanks to the created spatio-temporal models, the credibility of conventional predictive models generated by the mining company was validated, particularly in the areas with homogeneous structure of the rock massif. Noted deviations from the predictions were recorded in the areas with complicated structural-geological situation that is not considered in the calculation of the prediction models (Doležalová et al. 2009). In the future, it is therefore recommended to seek more suitable solutions of predictions for such complicated cases.

4.7 Prognosis of future subsidence development

The phase of subsidence desisting, which is characterized by a very gradual reduction in size of subsidence, may take even several years. For this phase, an outline of possible future subsidence development in the study areas by means of a regression analysis was suggested (Kajzar, 2011).

5 ADITIONAL SURVEYING AND MONITORING METHODS

To obtain additional knowledge about the deformation processes, verify the accuracy of the surveyed data, and obtain realistic ideas of the ongoing surface changes in a wider context of the studied area, methods of remote sensing were used together with the data from the geophysical, geomechanical and geodetic monitoring.

5.1 Remote sensing method - aerial photogrammetry

Aerial photogrammetry is a remote sensing method that allows determining the spatial position of studied elements with a surveying precision and its application may be suitable for monitoring the surface changes caused by underground mining and related reclamation. Repeated aerial photogrammetry at Louky locality showed the range and size of the surface changes (Fig. 3). The results from the aerial photogrammetry show that a large part of the scanned area is affected by mining. The method also enabled to observe the surface changes even in the areas of active reclamation (surface covered with mine spoils, flooded areas…) where land surveying is not possible (Kajzar et al. 2011).

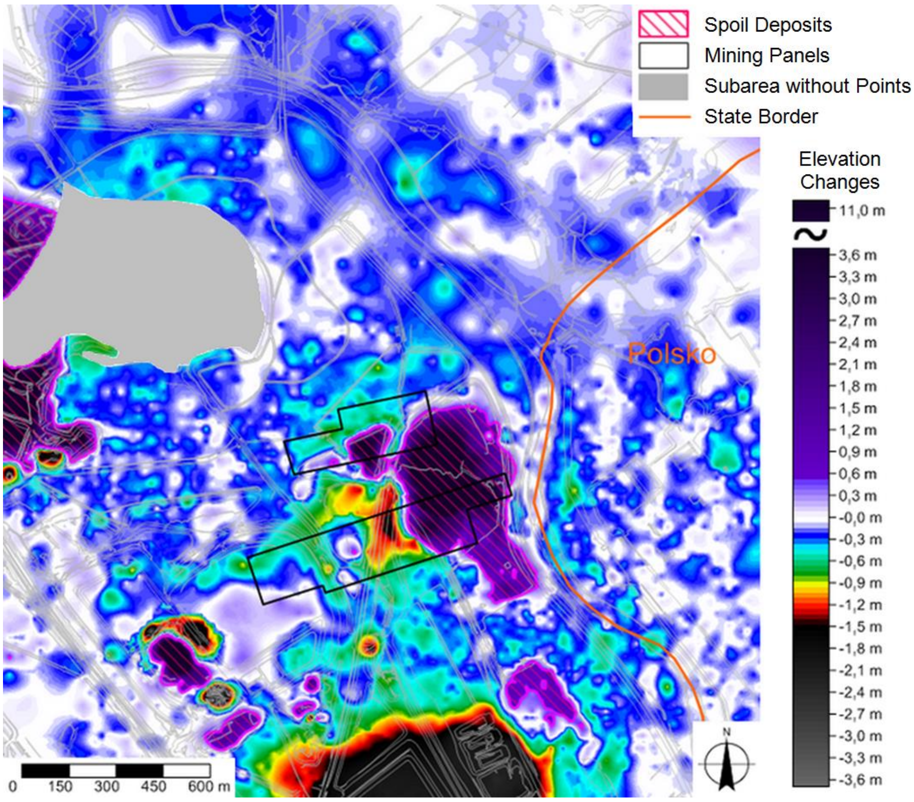

Fig. 3 Vertical changes between 2007 and 2009 generated from the aerial photogrammetry data in the Louky locality (Kajzar et al. 2012b)

5.2 Remote sensing method - radar interferometry

The method of satellite radar interferometry (Interferometry SAR – InSAR) was applied for the detection of subsidence for specific time periods. Using the differential interferometry SAR (DInSAR), it is possible to determine the extent of subsiding areas for the processed time period (up to few months). DInSAR results for consecutive time-periods display the spatio-temporal evolution of the mining induced subsidence.

In addition, the comparison of DInSAR and GNSS methods helped us to improve the values of subsidence and the delimitation of the area affected by subsidence in the studied locality (Kadlečík et al., 2012).

5.3 Geophysical methods - seismological observations

During coal extraction, induced seismic events are observed underground and/or on the surface as well. This seismic activity can significantly affect the progress of subsidence in the undermined areas, as was in the case of the seismological event in the Gabriela locality (Jiránková et al., 2013).

Therefore, seismological observations, which could continuously record and determine absolute units of seismic energy or magnitude were recommended to be, simultaneously, part of the subsidence depression research. On the other hand, seismology offers instantaneous dynamic and time dependent image of seismic regime in the investigated area.

5.4 Geomechanical methods - stress changes measurements

The stress detection using the CCBM probe (Compact Conical-ended Borehole Monitoring) is based on an accurate measurement of the deformations of a borehole conical bottom using an oriented strain gauge measuring probe. Then, using laboratory tests of mechanical properties of materials from the probe installation place, the deformations can be transformed into the shape of a stress tensor (Staš et al., 2011, Sugawara and Obara, 1999).

5.5 Geodetic method - precise levelling

It is a method of height surveying which uses the level instrument to determine the elevation between two points. By comparing the available data from the precise leveling with the GNSS data, the accuracy of the GNSS surveying method was verified. This method is also helpful for surveying small height changes that happen near the margins of the subsidence depression and also in the phase of the subsidence desisting. These small changes cannot be detected by less precise surveying methods (Doležalová, 2009).

Within the ICT project, the precise digital level instrument Sokkia SDL1X was acquired for the implementation of precise leveling combined with two three-meter and one-meter invar rods. At present, this instrument is used to perform more accurate measurements on the point profiles and also to verify the stability of slopes (Doležalová and Kajzar, 2012).

6 CONCLUSION

The purpose of this research is the creation of monitoring scheme using the combination of direct and non-direct surface surveying methods with other suitable additional methods and then the application of the proposed scheme to a real mining situation in selected part of the Upper Silesian Coal Basin. To reach this, GNSS and other geodetic, geophysics and remote sensing methods are combined.

At present, periodic surveying is repeated in the Gabriela locality (8 times per year) for the purpose of detailed research of the prolonged phase of surface subsidence desisting. In the Louky locality, only annual periodic surveying is currently repeated, in order to maintain the continuity of data series. The possibility of using a 3D laser scanner for the research of the problems of undermining is within our considerations now.

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RESUMÉ

Při hlubinném dobývání ložisek nerostných surovin dochází k vytváření volných podzemních prostor. Tyto prostory jsou následně vyplňovány masou nadložních vrstev, které se do nich prohýbají a prolamují. Probíhající přesuny materiálu se v případě vydobytí rozsáhlé plochy projevují až na povrchu, obvykle vytvořením kotliny poklesového charakteru. Pohyby a deformace, ke kterým při její tvorbě dochází, negativně působí jak na povrch, tak na objekty s ním spojené. Ačkoliv jsou teorie odpovídající potřebám hodnocení a prognózování pohybů a deformací povrchu nad dobývanými ložisky systematicky rozpracovány již déle než jedno století, stále není možné očekávané změny s jistotou dokonale popsat.

Snahou představeného výzkumu je na příkladu nově vznikajících poklesových kotlin demonstrovat možnosti využití moderních geoinformačních technologií pro zachycení skutečných časoprostorových změn povrchu spojených s tvorbou poklesové kotliny. To vychází z kombinace přímých i nepřímých měřických technik, zvláště metod využívajících globálních polohových navigačních systémů, doplněných o další geodetické, geofyzikální a geomechanické techniky a techniky dálkového průzkumu Země. Zjištěné údaje jsou následně vyhodnocovány v kontextu s geologickou a geomechanickou situací., s postupem těžebních prací a s očekávanými změnami povrchu.

Navržené postupy byly postupně aplikovány na dvojici vybraných těžebně aktivních oblastí. Obě lokality se nacházejí v Hornoslezské uhelné pánvi u Karviné v severovýchodní části České republiky. První lokalita, Louky, se nachází v dobývacím prostoru Dolu ČSM. Vybraná severní část této lokality se rozkládá na ploše cca. 6 km^2. Poslední období těžby zde začalo v roce 2006. V tomto období byly postupně do roku 2012 vydobyty čtyři horizontální poruby. Druhá lokalita, Gabriela, se nachází v dobývacím prostoru Dolu Darkov. Lokalita se rozkládá na ploše cca. 3 km^2. V lokalitě Gabriela bylo v červenci 2011 zahájeno dobývání posledního porubu. Ten se nachází ve sloji č. 40 s názvem "Prokop", která má celkovou mocnost asi 6 – 7 m. Pro sledování procesu vytváření poklesové kotliny nad exploatovanými uhelnými ložisky byly ve vybraných lokalitách vybudovány pozorovací stanice.

Pro zaznamenání prostorové změny stabilizovaných bodů obou pozorovacích stanic nejen během samotné těžby, ale také v obdobích mezi těžbou jednotlivých porubů (v případě lokality Louky) a během konečného období po ukončení všech těžebních aktivit, bylo využito GNSS, konkrétně systému GPS. GNSS je metoda, která může být na poddolovaném území úspěšně používána. Její výhoda oproti jiným běžným geodetickým metodám spočívá nejen v poskytování prostorových souřadnic zaměřovaných bodů, ale také ve schopnosti

rychle připojit poddolované území na stabilní oblast, která není ovlivněna poddolováním. Náš výzkum na sledovaných poddolovaných oblastech ukázal, že analýza vertikální i horizontálních pohybů umožňuje komplexnější a přesnější vyhodnocení povrchových změn a jejich příčin v horninovém masivu.

Data získaná metodou GNSS slouží jako vhodný zdroj vstupních informací pro analýzu povrchových změn ve sledovaných oblastech. Díky opakovanému použití této metody a také díky stabilizaci bodů pozorovací stanice ve formě profilů a roztroušených bodů je možné vyhodnotit průběžný vývoj poklesů a horizontálních posunů jednotlivých bodů, stejně jako celé sledované oblasti.

Efektivní práci se získanými údaji umožnily moderní programové prostředky geoinformatiky doplněné o účelově vytvořené programové nástroje (skripty, nádstavby, aplikace). Tyto nástroje pak umožnily s pořízenými daty provádět velmi zajímavé prostorové analýzy - analýza časového vývoje poklesu bodů, hodnocení liniových profilů, analýza horizontálních posunů, analýza časového vývoje poklesů a posunů bodů v závislosti na postupu porubní fronty, modelování časoprostorového vývoje povrchu, srovnání predikce poklesů se skutečným stavem, prognóza budoucího vývoje poklesu bodů.

Pro zajištění doplňujících poznatků o přetvárných procesech, ověření přesnosti naměřených dat, získání reálnější představy o probíhajících povrchových změnách celé oblasti v širším kontextu studované oblasti bylo využito metod dálkového průzkumu Země – letecké fotogrammetrie a radarové interferometrie a rovněž údajů z geofyzikálního, geomechanického a geodetického monitoringu.

V současné době jsou prováděna pravidelná měření na lokalitě Gabriela (8x ročně) za účelem detailního postihnutí dlouhotrvající fáze doznívání poklesů. Na lokalitě Louky se provádí v současnosti pouze roční periodické měření, za účelem zachování kontinuity datové řady. V rámci úvah zůstává možnost využití laserového 3D skeneru pro řešení zvolené problematiky.