A review of geodetic and remote sensing methods used for detecting surface displacements caused by mining

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Abstract. The paper describes the main development trends of methods for determining surface displacements (deformations) resulting from the phenomenon of induced seismicity by mining operations. Due to the unpredictable and sudden nature of induced seismicity, it is difficult to make measurements of displacements by traditional geodetic methods. In order to determine the methods used to determine surface displacements, an extensive review of current scientific literature was carried out. The scope of the analysis included methods for measuring deformations in mining areas during and after mining. Based on the review of over a dozen research papers, geodetic and remote sensing methods are presented, which are used to determine surface displacements at a lower or higher intensity. The analysis of the methods concerned in particular: leveling, Global Navigation Satellite System (GNSS), satellite radar interferometry, airborne LiDAR and aerial photogrammetry. As a result of the analysis, it was found that the satellite radar interferometry is presently the predominant displacement detection technique.

1. Introduction
Surface deformations (displacements) are an important issue in mining because they have an adverse effect on the terrain and building structures. The issue of deformation in mining has been taken up in many scientific papers [1-11], whose purpose was to learn about the deformation process and their analysis, determine the impact on building structures and develop methods to reduce deformation in mining areas. The form of deformation depends on the method of exploitation: underground and opencast because they affect the rock mass in a completely different way. In underground mining operations, the main causes of deformation are a change in water relations, displacement of rock mass and shocks of the rock mass (induced seismicity). The effects of underground mining are continuous and discontinuous deformations. The size and form of deformations depend mainly on: the depth of exploitation, the size of the selected space, the method of filling the post-mining void, the shape and size of the selected field, the speed of the mining front, the geological structure of the adjacent rock mass and the slope of the deck. Continuous deformation occurs when the surface layer bends over the selected space, this applies to large mining fields. To describe continuous deformations, Knothe's theory is used [12], which characterizes deformation indicators such as subsidence, slope of the subsidence pan, curvature of the subsidence pan, displacement and horizontal deformations of the surface. The above deformation rates are related to the distance from the edge of operation. However, discontinuous deformations do not accompany every operation, they can appear during and after
several dozen years from the end of the operation. Their occurrence is not preceded by any signs and the course is fast.

The occurrence of surface displacements is impossible to eliminate, therefore it is important to monitor mining areas and surrounding areas, which are also exposed to negative impacts of mining activities. To date, the methods used to measure displacements in mining areas are geodetic methods and remote sensing methods: leveling, Global Navigation Satellite System (GNSS), Light Detection and Ranging (LIDAR), aerial photogrammetry and satellite radar interferometry (InSAR). In addition, hybrid methods are also used combining two techniques, e.g. InSAR and GNSS, leveling and GNSS, which are complementary measurements made with one technique. Measurements of displacement by geodetic methods are performed periodically and are a source of basic information about deformation. Observations are aimed at determining the location and values of deformations to, on this basis, e.g. prepare forecasts of future deformations or estimate the impact of deformations on surface objects. However, traditional geodetic methods (leveling) are not suitable for measuring deformations due to induced seismicity [13,14] due to the unpredictable time and location of occurrence. Spontaneous induced shocks are characterized by a sudden and unexpected course which, as a consequence, may cause deformations of the terrain and even destruction of buildings. However, the development of measuring instruments and techniques, especially remote sensing measurements, has initiated a different way of determining surface displacement that deviates from typical terrain measurements performed by surveyors. The emergence of satellite radar interferometry has enabled the detection of past displacements.

The article analyzes the methods of determining surface displacements in underground mining areas on the basis of a review of extensive scientific literature in the context of geodetic and remote sensing methods. The main objective was to review the current state of knowledge regarding methods of monitoring deformations in mining, with particular emphasis on displacements caused by shocks induced by underground mining. The scope of the review concerned deformation detection methods during and after mining operations. The article is organized as follows: the next section contains a description of the method used to measure displacements along with examples, the last section discusses the advantages and limitations of the methods, as well as the conclusions of the literature review.

2. Methods for determining surface deformation
As mentioned in the introduction, measuring methods are divided into geodetic and remote sensing methods. Relevant literature was primarily found using the Google Scholar search engine. When searching for scientific studies (books, articles, other scientific materials), the following keywords were used: deformation, subsidence, displacement, underground mining, induced seismicity, geodetic survey and, respectively, the names of methods for determining deformation. The temporal search range was adopted from 1980 to 2020. In the results obtained, the methods of satellite radar interferometry were ahead. Below is a short description of individual methods with examples of their use.

2.1. Leveling
In geodesy, leveling is the basic method of height measurement used since the mid-19th century. For several decades, it has been used in mining to measure deformations caused by ongoing or terminated mining. Measurements are made periodically and relate to points located in strictly defined leveling sequences. Usually, the measurements are made at several monthly intervals. The accuracy of this method is below a millimeter, but it depends on the equipment used. Leveling is also used to measure deformations in cities under the influence of exploitation. Table 1 presents the tests using leveling.
Table 1. Case studies in which levelling was used

| Source/year | Area of research | Mineral | Status of mine | Measurement time | Results | Comments |
|-------------|------------------|---------|----------------|------------------|---------|----------|
| [15]/2001   | Poland, LGCD*    | copper  | active         | measurement before and after shock | subsidence -150 mm induced shocks on 11 April 2000, energy 2,5x10⁹ J |
| [16]/2005   | Poland, USCB**   | coal    | active         | February 1999 to February 2001 (every two months) | subsidence daily of benchmarks from -10 mm to -1 mm additionally seismic refraction measurement |
| [17]/2011   | Turkey, Zonguldak-Kozlu | coal    | active         | 10 months | subsidence from -25 mm to -35 mm impact of exploitation on the nearby city of Kozlu |
| [18]/2013   | Poland, Wałbrzych | copper and coal | finished | 1967, 1973, 1974, 1979, 1988, 1994, 2004, 2005, 2006, 2007 | max. subsidence 709.6 mm and max. uplift +89.7 mm observation of secondary deformations |
| [19]/2013   | China, Huaibei    | coal    | active         | January 2009 to March 2011 | subsidence ca. – 0,80 m with the InSAR method |

* Legnica-Glogow Copper District  
** Upper Silesian Coal Basin

Cyclical leveling measurements provide deformation monitoring in mining areas, which is necessary to plan the progress of exploitation and safeguards that minimize the impact on the surface and building structures. The measurement requires appropriate weather conditions and is time consuming. However, the results obtained refer to a significantly limited area. Leveling results are very often a reference measurement to which measurement results made with other methods are compared, e.g. GNSS, InSAR. Leveling could be used to measure displacements caused by induced shocks because it ensures a high accuracy of measurements. But it requires a lot of work and the results are limited to measuring points only. In addition, the time resolution is too long to register any shocks.

2.2. Aerial photogrammetry

Aerial photogrammetry is widely used to determine surface displacements in mining areas. Like leveling, the beginnings of aerial photogrammetry date back to the mid-19th century. This method is primarily used for inventory of open-cast mines, but also for monitoring the surface of underground mines (Table 2). In recent years, unmanned aerial vehicles (UAVs), which are operated remotely by an operator on the ground, have been popular carriers of digital cameras. The resolution of the acquired images depends on the camera parameters. Aerial photogrammetry measurements enable the generation of orthophotos or digital terrain models (DTM). The accuracy of the results on the basis of optical images is from a dozen to several dozen centimeters. The main limitation of the accuracy and the possibility of using the acquired data is related to the vegetation coverage of the monitored areas.

Table 2. Case studies in which aerial photogrammetry was used

| Source/year | Area of research | Mineral | Status of mine | Measurement time | Results | Comments |
|-------------|------------------|---------|----------------|------------------|---------|----------|
| [20]/2011   | Czech Republic, USCB | coal    | active         | from 2007 to 2009, spring (each year) | surface changes from -3,6 m to +11,0 m additionally GNSS measurement, measured area 2,5x2,5 km, DTMs with resolution 10 cm measured area ca. 110 h |
| [21]/2020   | Poland USCB      | coal    | active         | March, April; September 2016; April 2017 | subsidence from -2,5 m to +0,25 m | |
February 2020

[22]/2020 Velenje, Slovenia coal active from February to October 2017 subsidence of points from -2.5 m to -5.9 m additionally GNSS and tachymetry measurements

[23]/2020 Mongolian coal active June, September, October 2018 subsidence from -2.6 m to -0.20 m measured area ca. 1.66 km², 560 images, additionally GNSS and total station measurements

Aerial photogrammetry provides information about the terrain for the entire studied area and is treated as another method for observing surface geometry and their changes, especially since it allows measurement of extensive areas and hard-to-reach places. Determining the terrain deformation by this method, apart from taking pictures, also requires establishing and measuring Ground Control Points (GCP), which are necessary for reference in the space of measurements made. Measurements by aerial photogrammetry are not cyclical. Usually, they are made in connection with individual orders, which refer to specific cases. Aerial photogrammetry results are often integrated with GNSS measurements. The use of aerial photogrammetry to measure displacements caused by induced seismic would ensure the continuous presentation of results (mapping of the subsidence area), but accuracy is sufficient. In addition, weather conditions, time of day and vegetation limit measurements. In addition, the lack of cyclical measurements at short intervals will not ensure the capture of the terrain surface before and after the shock.

2.3. Airborne LIDAR
The first LIDAR measurements were made in the sixties of the 20th century. Airborne LIDAR is used to reproduce the relief, development and objects on the surface. The research presented in Table 3 also shows that the method is also used to detect surface displacements in mining areas. The laser scanner provides measurements in the form of points, where each point contains coordinates X, Y, Z (3D space). The resolution of the measurements depends on the number of measured points per one square meter of the surface. Usually, the accuracy of the DTM is from a dozen to several dozen centimeters.

| Source/ year | Area of research | Mineral | Status of mine | Measurement time | Results | Comments |
|--------------|------------------|---------|----------------|-----------------|---------|----------|
| [24]/2005    | Papua New Guinea, Lihir | gold    | active         | August 2004     | geomorphology mapping of mine area | 9,578,830 points, DTM with 2 m resolution |
| [25]/2008    | Canada, Alberta   | coal    | finished       | 24 July 2005    | mapping of coal mine subsidence locations | measured area 33 km², additionally PSInSAR (subsidences from -2.3 to +4.1 mm/year), mesh size: 0.5 m, 1 point per square metre |
| [26]/2010    | Australia, Mandalong | coal    | active         | 18 June 2003, 12 August 2006, 10 June 2008 | subsidence from measured area 6 km², DTM with 2 m resolution |
| [27]/2017    | Poland, Bytom     | coal    | active         | 9 March 2010, 18 April 2011, 26 May 2012 and 15 May 2014 | subsidence from -2200 mm to 20 mm | 8 points per square meter, additionally levelling measurement |
As in the case of aerial photogrammetry, LIDAR enables the measurement of large areas together with places where the use of classic geodetic measurements is impossible. LIDAR makes it possible to record the entire deformation surface, but nevertheless, measurements with this method are performed relatively rarely. In this case, vegetation is also a problem because it limits the number of surface points measured, especially in areas with dense plating. Therefore, LIDAR measurements are not sufficient to determine the displacement caused by induced seismic in areas of underground exploitation.

2.4. GNSS
Satellite navigation has become public since 1980. The GNSS / GPS method is used to monitor deformations in mining areas that have arisen under the influence of long-term operation and induced shocks (Table 4). Measurements by this method offer an advantage over traditional ground methods due to the high temporal and spatial resolution. GNSS provides coordinates of measured points in 3D space that can be obtained with millimeter accuracy. GNSS enables the measurement of large areas, and thanks to observation networks (stations) located throughout the country or mining area, it is possible to continuously measure surface movements. GNSS measurements at permanent stations, where observations are made constantly after a period of about 5 years, allow determining the velocity of station displacement in a given system and disturbances not related to the long-term trend.

| Source/year | Area of research | Mineral | Status of mine | Measurement time | Results | Comments |
|-------------|------------------|---------|----------------|------------------|---------|----------|
| [28]/2009  | Czech Republic, USCB | coal | active | from 2006 to 2008 (repeated measurements) | max. subsidence -100 cm | observation network built, multiple determination of the spatial position of points, additionally the Budryk-Knothe method |
| [29]/2011  | China, Inner Mongolia | coal | active | from September 2008 to July 2009 | max. subsidence -3,0 m | control network contains 23 points, additionally updated DEM |
| [30]/2015  | Poland, LGCD | copper | active | February 2010 and March 2013 | displacements ca. -3 mm* and -6 mm** | network ASG-EUPOS (permanent stations), two induced shocks: on 9 February 2010* (1,9x10^6 J) and on 19 March 2013** (1,6x10^8 J) |
| [31]/2019  | Poland, USCB | coal | active | from 5 December 2018 to 4 March 2019 | displacements -10,0 cm/year | GNSS EPOS stations, induced shocks during the study period, additionally InSAR technique |

During the measurement, visibility between stations is not necessary, which gives more flexibility in choosing the location of the station than in the case of ground surveying. Measurements can be carried out both day and night, in various weather conditions. After all, measurements using this method are not a basic measurement to determine surface displacements in mining areas. The advantage of GNSS is the continuous measurement of station coordinates and a high level of accuracy, thanks to which it is possible to determine the displacements caused by induced shocks.

2.5. Satellite radar interferometry (InSAR)
The InSAR method has been used since 1990. Satellite radar interferometry uses satellite imagery acquired from two different times to determine the difference between the electromagnetic wave phases. The phase shift of the radar signals appearing in the same place indicates the occurrence of terrain
displacement (change in relative elevation). For several decades, radar satellite interferometry has been growing rapidly due to the increasing number of radar satellite missions that often acquire 1 meter resolution earth images (TerraSAR-X satellite). However, the accuracy of displacement results is determined at the level of millimeters. Although the satellites constantly monitor the surface of lands and oceans, the timeliness of new data is several days, e.g. for the Sentinel-1 mission, the time interval is 6 days. Satellite radar interferometry provides a research of past surface displacements if radar imagery for a given period is available. This advantage makes it possible to research displacements caused by induced seismicity (Table 5), which is impossible with other measuring methods.

Table 5. Case studies in which satellite radar interferometry was used

| Source/Year | Area of research | Mineral | Status of mine | Measurement time | Results | Comments |
|-------------|------------------|---------|----------------|------------------|---------|----------|
| 2004 Australia, Sydney | coal | active | from August 1993 to January 1996 | LOS displacements: from 0 to -30 mm (8 Mar - 4 Jun 95) | displacements resulting from ongoing exploitation, JERS-1 and ERS-1/2 satellites, DInSAR method |
| 2013 Poland, USCB | coal | active | from 1992 to 2003 | LOS displacements from -5 to -15 mm/year | induced shocks with energy from $10^5$ J to $10^9$ J, which occurred in 1992-2003, ERS-1/2 and ENVISAT satellites, PSInSAR |
| 2017 China, Yuanbaoshan District | coal | active | from December 2015 to May 2016 | LOS displacements exceed 5 mm | displacements resulting from ongoing exploitation, Sentinel-1A/B satellites, DInSAR method |
| 2017 Botswana | natural gas | active | 30 March 2017 and 11 April 2017 | LOS displacements ca. -5 cm | induced shock on 3 April 2017 (Mw = 6.5), Sentinel-1A/B satellites, DInSAR method |
| 2018 USA, Oklahoma | natural gas | active | terms of imagery before and after the shock | LOS displacements ca. -5 cm | three induced shocks on 2016: 13 February, 3 September, 7 November (Mw ≥ 5.0), Sentinel-1 satellites, DInSAR |
| 2018 Iceland, Hellisheidi geothermal field | geothermal field | active | 30 June 2011 and 3 May 2012 | LOS displacements 2 cm | increase in induced seismicity in connection with fluid injection, TerraSAR-X satellite, DInSAR and GPS method |
| 2019 Poland, LGOM | copper | active | from 21 January 2016 to 22 December 2016 | LOS displacements up to –80 mm | induced shock on 29 November 2016 (Mw = 4.2), Sentinel-1A/B satellites, DInSAR and SBAS method |
InSAR enables detection of displacements between two images (by the DInSAR method), but also in a time series of many radar images (the SBAS method, PSInSAR). Time series generate displacements that have arisen over a longer period of time covering several months / several years and their spatio-temporal development. The main limit in this method is vegetation in research areas and the impact of the atmosphere. Nevertheless, the scientific papers presented above indicate that InSAR is the most commonly used method for measuring displacements caused by induced seismicity.

3. Discussion
The above section presents short descriptions and selected examples of the use of the most commonly used methods to determine surface displacements in underground mining areas. The scientific research cited in the tables best matches the keywords used. As mentioned earlier, the review of the current state of knowledge was to serve the selection of the measurement method that would allow determining the impact of mining tremors (induced seismicity) on the surface of the land. The analyzed studies were significantly associated with the impact of long-term operation on the earth's surface [39, 40]. Single studies, both in the leveling method [15] and GNSS [30, 31], concerned the measurement of deformation due to induced shock. However, the method of satellite radar interferometry proved to be the most commonly used technique in the case of induced seismicity [32-38]. In many studies, a combination of methods, e.g. InSAR and GNSS, InSAR and leveling, aerial photogrammetry and GNSS was used to measure displacement. Precision leveling is the oldest geodetic method. However, it is considered to be the most accurate of all the techniques presented [15-19]. Measurements with this method are carried out periodically (e.g. every six months) in mine areas because they provide basic information about surface deformations. But this method is limited only to leveling sequences and requires a lot of work, especially in field measurements. A comparable level of accuracy for leveling has GNSS measurements, which require continuous observation (about 5 years) to establish correct results on established stations or permanent station networks.

Aerial photogrammetry and LIDAR measurements are characterized by the ability to quickly measure for vast areas and places inaccessible to humans. They show much lower accuracy, but they reflect all the characteristic features of the studied area, including the entire geometry (shape) of deformation [20-27], and not, as in the case of leveling and GNSS, only the heights related to measuring points. Aerial photogrammetry and LIDAR measurements are usually carried out on request and concern the acquisition of an orthophotomap or DTM. Limiting the use of data in these measuring methods is caused by the occurrence of vegetation in the studied area. The same problem occurs in satellite radar interferometry, where vegetation affects low coherence, and this is associated with obtaining incorrect displacement results. Another limitation of InSAR is the negative impact of the atmosphere on measurements due to its heterogeneity. But despite this, InSAR has many advantages, thanks to which it excels among the methods of measuring surface displacements. First of all, it enables the study of historical phenomena, which is extremely important especially in the case of induced seismicity because before the occurrence of shock the epicenter is unknown. Measurement accuracy is similar to leveling and GNSS measurements. InSAR does not require cash outlays or direct field measurements. Satellite imagery is widely available thanks to the European Space Agency's Sentinel-1 satellite mission and observing the surface from space level covers vast areas and hard-to-reach places. In addition, the use of time series, e.g. the SBAS method, allows the determination of the spatio-temporal development of surface displacement over a long time (several months / years).

4. Conclusions
Each of the methods presented above has various types of restrictions resulting from the equipment used, the research area or atmospheric conditions. But due to the knowledge of the subject of these restrictions, measures are taken to eliminate or minimize (e.g. appropriate measurement method, data filtering, atmospheric corrections) their impact on measurement results. Therefore, it is necessary to select the appropriate measurement technique for the phenomenon under study. In the case of induced
seismic, satellite radar interferometry works best, which stands out from the rest of the methods. The biggest advantage of this method is the ability to measure seismic events that have occurred in the past. In addition, InSAR does not require large financial outlays, as well as the time and employee outlays. Despite its limitations related to areas covered with vegetation, InSAR is able to provide good quality results. An additional advantage is the ability to determine the spatio-temporal development of displacements based on time series, e.g. the SBAS method. The development trend of methods for measuring displacement in mining areas is primarily focused on remote measurement methods, which requires human intervention only in the development of final results. This situation is caused by new technologies, the rapid development of the space sector, but also by universal access to radar images and software.

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