# Monitoring of land surface movements in a seismically active post-mining area during mine closure - A case study

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The process of mine closure is accompanied by numerous hazards, including among others deformation hazards and post-mining seismicity hazards. Water is a factor that may activate the development of seismicity during mine closure, especially at the stage of the mine flooding process, which influences changes in the geodynamic stability of the rock massif. A seismic phenomenon may cause unexpected movements of the surface, which may affect the stability of facilities and critical infrastructure. In order to deepen the knowledge of post-mining seismic phenomena in relation to surface deformation, a European research project is currently being implemented. The project involves monitoring of surface deformation and recording post-mining seismic phenomena on a testing site in Poland, located in the area of the currently flooded hard coal mine Kazimierz-Juliusz. The paper presents an innovative, automatic system for measuring and processing results, developed for the needs of the research, based on high-frequency and multi-system Global Navigation Satellite System observations, using the relative method for precise position determination. Observations are verified on the basis of periodic angular-linear and levelling control measurements. The paper also presents the methodology of monitoring implementation, and a preliminary analysis of surface movements in relation to selected registered seismic phenomena.

**Keywords:** Seismic activity, post-mining, GNSS monitoring, ground deformation

## INTRODUCTION

The process of mine closure is accompanied by numerous hazards that have a decisive impact on the state of public safety, including deformation hazard, water and flood hazards, gas hazard and the post-mining seismicity hazard. During mine closure, the seismic hazard in the initial phase is associated with works related to the disassembly of machinery and equipment, the construction of filling plugs or isolation and retaining plugs, isolation dams and backfilling the shafts. As shown, an additional factor that may activate the development of seismicity during mine closure is water, in particular at the mine flooding stage, which influences changes in the geodynamic stability of the rock mass. When there is a dense network of unsealed workings in the rock mass after the mine has been closed, when the not-backfilled workings are at shallow depths or when there are voids in the rock mass above the unsealed workings, the risk of post-mining seismicity becomes of particular importance. A seismic phenomenon may cause unexpected movements of the surface, which may affect the stability of the facilities and the critical infrastructure. For the correct assessment of the possibility of such movements, it is primarily important to register seismic events in the period after the closure of the mine. Unfortunately, when the mine decommissioning commences, the geophysical station is shut down, which means that the number of measurements in terms of the seismic hazard of the post-mining areas is reduced.

A European research project is currently being carried out to deepen knowledge of post-mining seismic phenomena with the main objectives of investigating the relationship of post-mining seismicity to surface deformation, developing methods for long-term monitoring of post-mining areas, and international guidelines for managing and mitigating the risk of seismic events in post-mining regions. The results of the research conducted so far have been presented in a number of publications (Dominique *et al*., 2022; Jirankova and Konicek, 2022). As part of this project, continuous monitoring of surface deformation and recording of seismic phenomena are carried out at a test site in Poland, located in the area of the currently flooded hard coal mine Kazimierz-Juliusz.

This paper presents an innovative, automatic system for measuring and processing results, developed for the purposes of the above-mentioned research, based on the high-frequency and multi-system Global Navigation Satellite System (GNSS) observations. The proposed solution is based on the Global Positioning System (GPS) system with the support of Globalnaja navigacionnaja sputnikowaja sistiema (GLONASS) systems, the European satellite navigation system Galileo and the Chinese satellite navigation system BeiDou. Continuous monitoring of displacements in the study area is performed at single observation points with the use of multi-system GNSS receivers. Additionally, periodic angular-linear, levelling and static GNSS control measurements are performed on the observation line points, stabilised in the area of conducting continuous GNSS observation. The paper presents the monitoring methodology used, including the above-mentioned measurements and the results of preliminary analysis of observations in the period related to the occurrence of seismic activity in the studied area. The mining area of the Kazimierz-Juliusz mine is located in the eastern part of the Upper Silesian Coal Basin. The mining area of the mine is 23.5 km$^2$. The presence of quaternary and triassic as well as carboniferous deposits has been documented in the study area. The total thickness of the overburden documented by exploratory boreholes ranges from 0.5 m to 146 m. The deposit is traversed by a network of faults with longitudinal and latitudinal directions or close to them, with a maximum drop of 270 m. Faults divide the deposit into parts. The depth of the coal seams in individual parts depends on the location in relation to tectonic dislocations. Intensive mining exploitation was carried out in the area. The maximum depth of mining in the observed area was 700 m. Shallow mining was carried out in a significant part of the area. There was relatively high induced seismicity during the mining operation. In the years 1977-2015, exploitation carried out in the study area induced about 200 seismic events with energy above $10^5$ J ($M_L \approx 1.7$ magnitude). After the closure of the mine, in the years 2018-2020, several seismic events with a magnitude of around 2 were recorded in this area. In the period from the start of the project, i.e., from September 2020 to December 2022, 12 seismic events with a magnitude ranging from 0.8 to 2.1 were recorded.

**Research methodology**

The design of the spatial observation network of surface movements was developed using analyses of the deformation-strain (energy) states of the rock mass in the study area and the mining carried out. The course of faults and the possibility of stabilising observation points in the field were also taken into account. The developed network design was implemented. The network consists of a dedicated GNSS continuous monitoring network (including monitoring stations Nos. 8104, 8105, 8106) and 34 observation points where control, periodic angular-linear, levelling and periodic GNSS measurements are carried out. Thirty-four observation points create the measurement line, the course of which is designed so that it passes over the outcrop of the Feliksowski fault zone located in this area, which drops the layers by 200-250 m towards the NW and the NE-SW direction. The location of monitoring stations and observation line points in the field against the background of the contours of exploitation is shown in Figure 1.

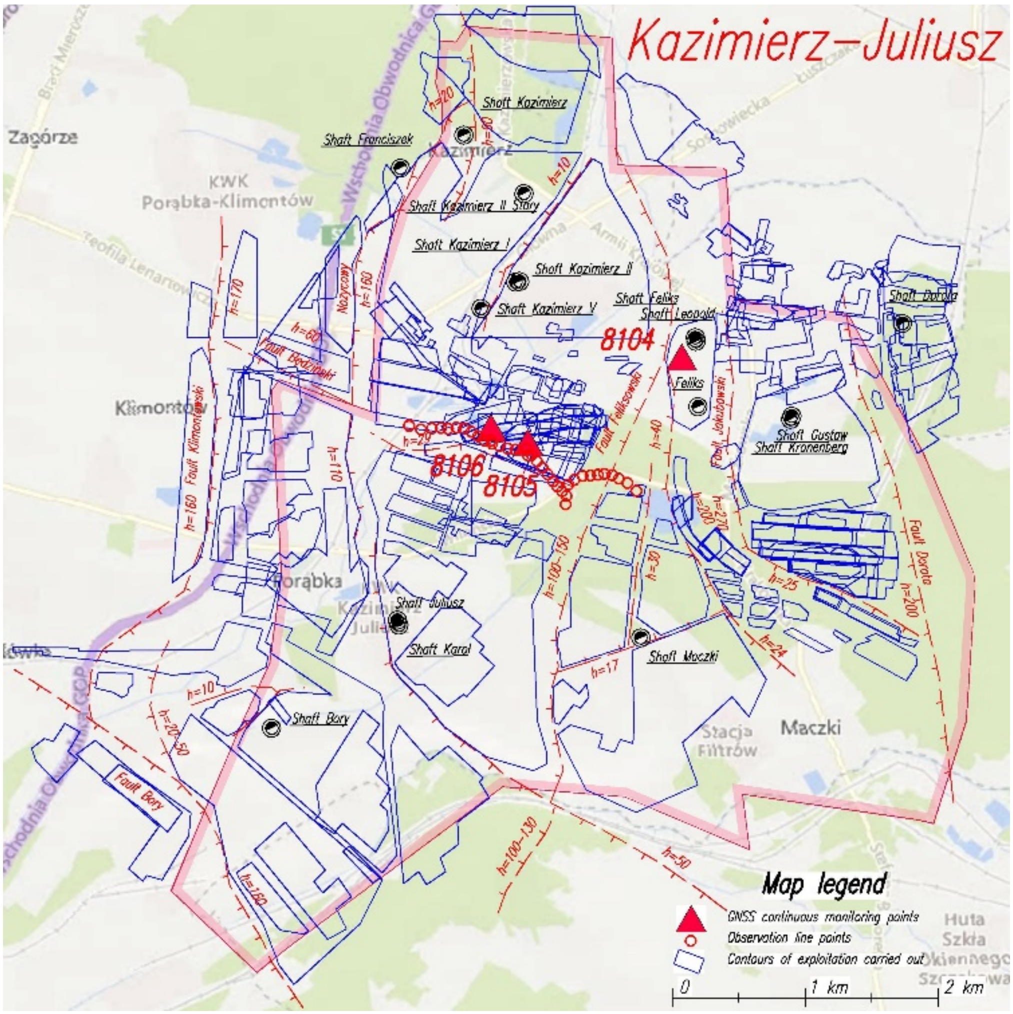


*Figure 1. Location of monitoring stations and observation line points in the field overlaid with the mine map of the area.*

Continuous monitoring of surface movements is carried out with the use of the automatic measurement and GNSS observation system developed under the project. The proposed monitoring system (implementing continuous monitoring) is based on high-frequency and multi-system satellite observations and it uses the relative method to precisely determine the position. This method is based on double differentiation of observations and provides the most accurate way to determine GNSS coordinates for short vectors. It consists of the simultaneous processing of data from two or more monitoring stations. Such a solution enables the elimination or significant reduction of important factors such as clock errors in the satellites and receivers, atmospheric delays, etc. (Kleusberg, 1986). The system is an innovative solution, because it integrates geodetic measurements with the use of many navigation systems with the module of data processing and visualisation of results in the study of land surface movements in seismically active post-mining areas. The use of multi-system, high-frequency GNSS observations from four global positioning systems (GPS, GLONASS, Galileo and BeiDou) ensures high accuracy of measurements. The developed system, in addition to high accuracy and reliability of displacement determinations in a short time, also ensures high efficiency and functionality while ensuring an appropriate level of safety. The system consists of four basic modules, which include a measurement module - observation network, a module for collecting, controlling and pre-processing observations, a module for processing and developing observations (the main element of the system), and a module for reporting and presenting results. The implementation of individual system functionalities is carried out with the use of the Trimble 4D Control software. The block diagram of the applied system is shown in Figure 2.

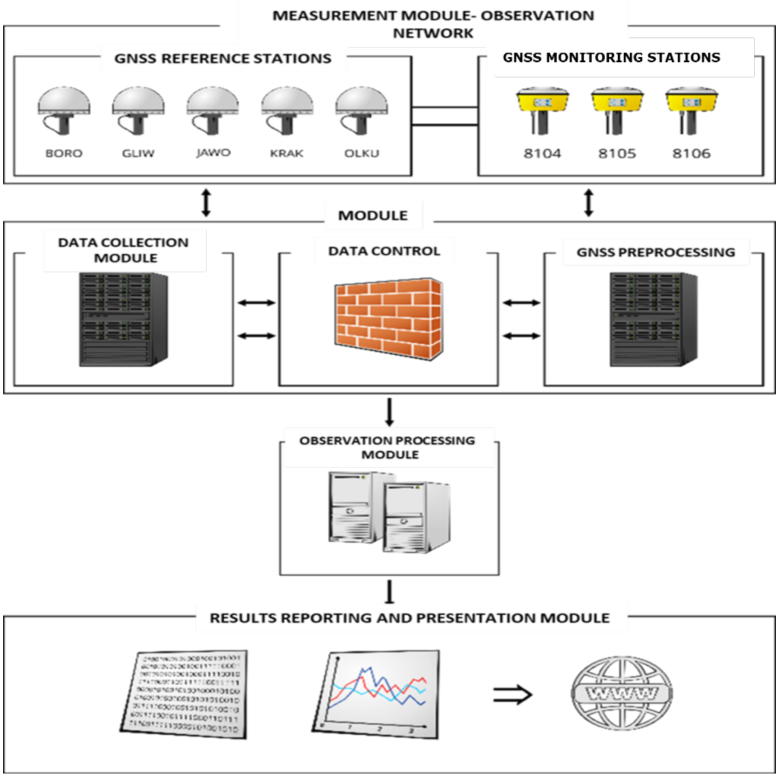


*Figure 2. Block diagram of the construction of an automatic measurement system and the development of GNSS observations in the Kazimierz-Juliusz mine.*

The core element of the continuous observation data acquisition module is a dedicated GNSS monitoring network. This network consists of two types of measuring stations. The first are the stations located in the study area; these are three monitoring stations (80104, 8105, 8106), which are treated as designated stations, used to study the ground surface movements and possible seismic or paraseismic events. The second type are reference stations, which are reference points for monitoring stations. They are located outside the impact area of mining exploitation in order to ensure the stability of the reference system. The network of reference stations consists of a total of five permanent stations located approximately 8.3 km to 49.2 km from the monitoring stations. The reference stations JAWO and BORO belong to the commercial VRSNET network, GLIW and OLKU are stations of the commercial TPI Net Pro network, while the KRAK station is the reference, scientific and research station, belonging to the University of Agriculture in Krakow. A sketch of a dedicated GNSS monitoring network is shown in Figure 3.

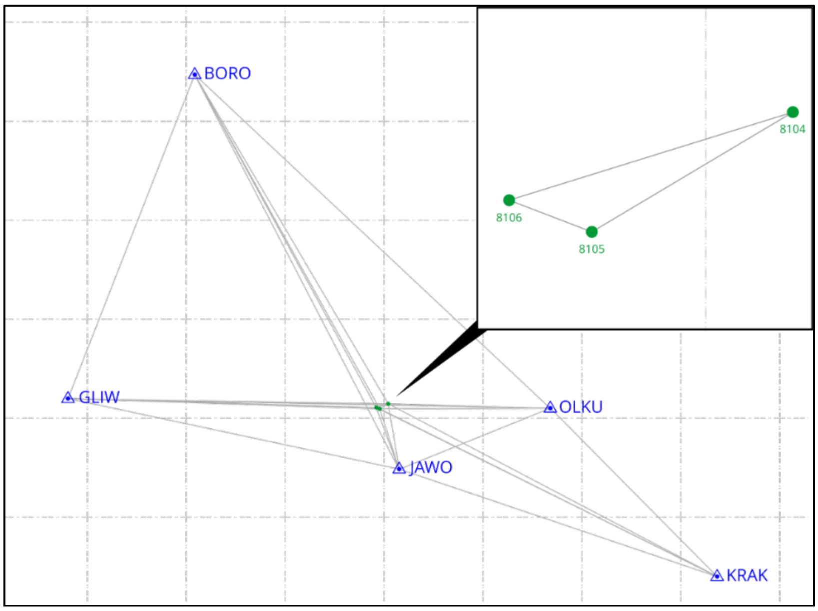


*Figure 3. Sketch of the GNSS monitoring network at the Kazimierz-Juliusz facility.*

The research uses four types of GNSS receivers. Monitoring stations 8104, 8105, 8106 are equipped with TRIMBLE NETR9s receivers with Zephyr 3 Rover antennas. In addition, each monitoring station was equipped with a Moxa communication module, based on GSM technology, an APC BX500CI UPS emergency power supply module and an industrial camera for visualisation and monitoring of the GNSS antenna. These receivers are dedicated to work in a remote network, access to which is provided via a website using a GSM communication module. This solution provides remote access, configuration and management of the receiver's operation.

Before the commencement of continuous GNSS observations, the system was validated in order to obtain high accuracy of coordinate changes at the monitoring stations (Sokoła-Szewioła and Siejka, 2021). The initial coordinates of the stations were determined by static GNSS measurement with post-processing. GNSS observations performed at measurement stations (monitoring and reference) are saved in the form of hourly observation files in the internal memory of receivers, and then, using communication modules, sent by the server to the data repository. Subsequently, the raw observational data is converted to the RINEX 3.03 format by means of the conversion and pre-processing module. At the same time, using the Ephemeris Manager, navigation files are generated for all observed GNSS satellites necessary for the estimation of station coordinates. The main module of the system implementing the development of high-frequency GNSS observations in the post-processing mode (Post Processing Engine) was based on the relative positioning method. The compilation of the observations on the designated points is performed each time as a network solution in relation to five reference stations. The solution uses algorithms for precise determination of point coordinates based on multi-GNSS observations, taking into account the problem of modelling inter-system hardware delays of receivers

Periodic control angular-linear and levelling measurements on the stabilised observation line points in the area of continuous monitoring are carried out as planned, once a quarter and after the occurrence of a seismic event, the epicentre of which is located near the monitoring system implemented in the field. In order to determine the coordinates of plane points of the observation line, classical angular-linear measurements are performed. The coordinates of the tie points were determined based on the results of static GNSS measurements and the post-processing performed on their basis. In addition, periodic static GNSS measurement is carried out in order to control the accuracy of the measurements. Measurements of the height differences between the measuring line points are made with the use of precision levelling.

Plane and elevation coordinates are calculated by strict alignment in the national spatial reference system.

## RESULTS AND DISCUSSION

During the observation of land surface movements in the area of the mining area of the Kazimierz-Juliusz mine, i.e., from December 2020 to December 2021, 12 seismic events with energies ranging from $10^3$ J to $10^5$ J (magnitude M from 0.8 to 2.1) were registered. The location of event epicentres in the mining area of the mine is shown in Figure 4. Ten phenomena were analysed due to the fact that the full registration of the surface movement detection took place after the validation period, and then full stabilisation of the continuous monitoring points.

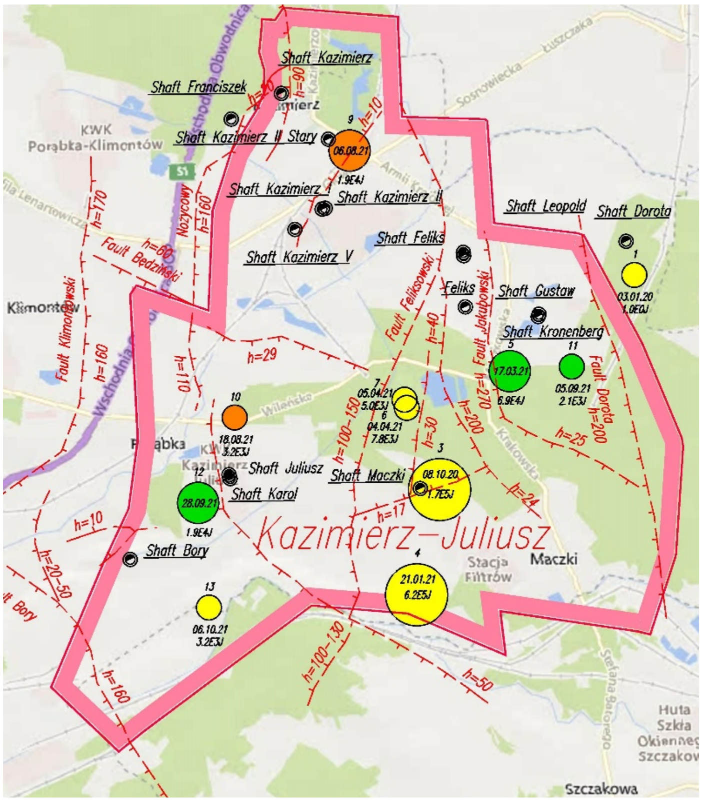


*Figure 4. Location of seismic event epicentres registered in the mine area from September 2020 to December 2021.*

The analyses included seismic phenomena, the epicentres of which were located in the area of the mine. The results of the analysis of continuous observations showed significant surface movements in the time period associated with the occurrence of two seismic phenomena with magnitudes M = 1.1 and M = 1.0 recorded on 4 and 5 April, 2021. Epicentres of these phenomena are located in close proximity to the points of the observation network (about 500 m).

Figures 5 and 6 show a graphic visualisation of the results of measurements of height changes at the points monitored with the GNSS technique No. 8105, 8106 in the period from 1 to 15 April, 2021, located near the observation line for control measurements, over the area where particularly intensive exploitation was carried out. The period presented in the diagrams also covers the seismic events on 4 and 5 April, 2021. The presented time series of changes in the height of monitored points are based on network solutions in post-processing, implemented through an automatic monitoring system built for the needs of the project.

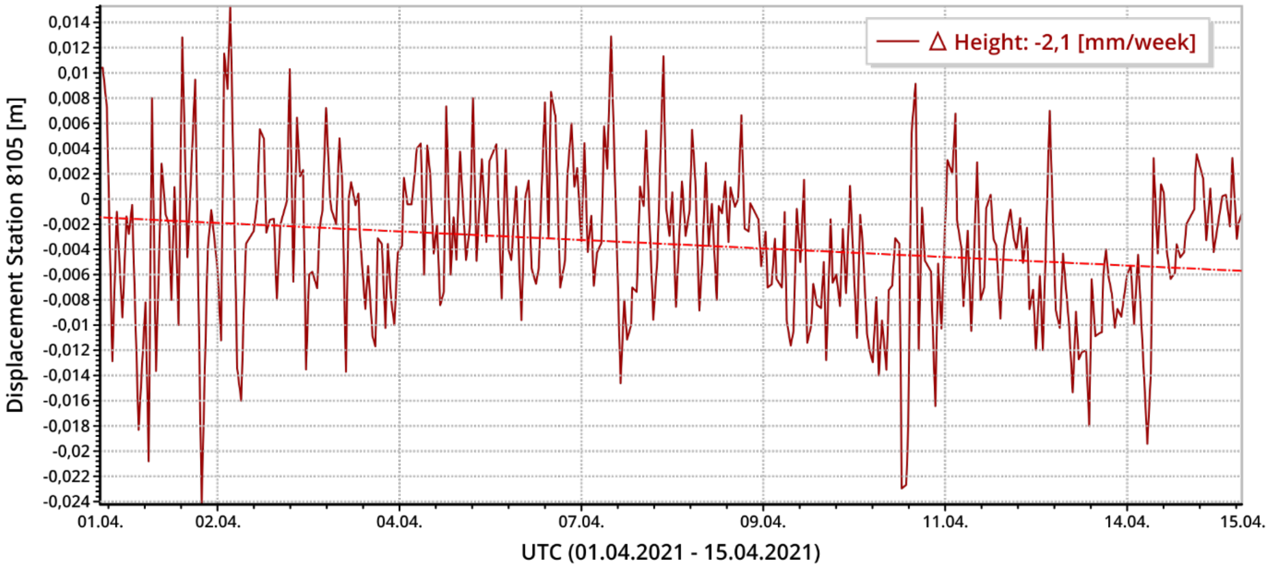


*Figure 5. Graph of the time series of height displacements (H) for the point 8105 (04/01/2021 - 04/15/2021). Displacement trend line (red).*

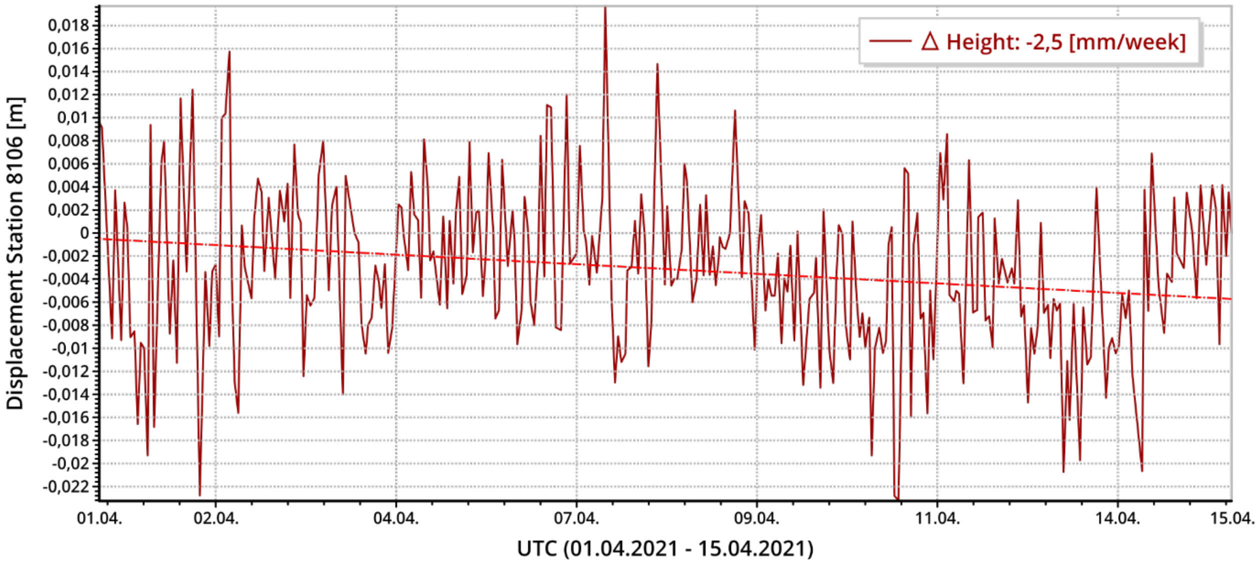


*Figure 6. Graph of the time series of height displacements (H) for the point 8106 (04/01/2021 - 04/15/2021). Displacement trend line (red).*

For a more detailed analysis of the impact of the above-mentioned seismic phenomena on the surface of the studied area, a detailed analysis was performed for these events, covering the period immediately before and after the occurrence of the events. These analyses covered the full 24-hour period in which the event occurred, and were based on basic hourly solutions implemented continuously in post-processing. In addition, they were supplemented with high-frequency real-time real time solutions implemented with high time resolution of 1 sec. Figures 7 and 8 summarise the time series of solutions for monitoring stations (8105, 8106) for the height component. The diagrams show the moment of the seismic event of the first analysed phenomena (04/04/2021) according to the GPS time (minus 1 h in relation to the local time of the place of observation). The time series were elaborated. Systematic errors were removed and an additional time series of 'measurement noise' was determined. The calculated average measurement error of the height coordinate in the analysed time period was 2.8 mm at the monitoring station 8105 and 3.2 mm at the station 8106.

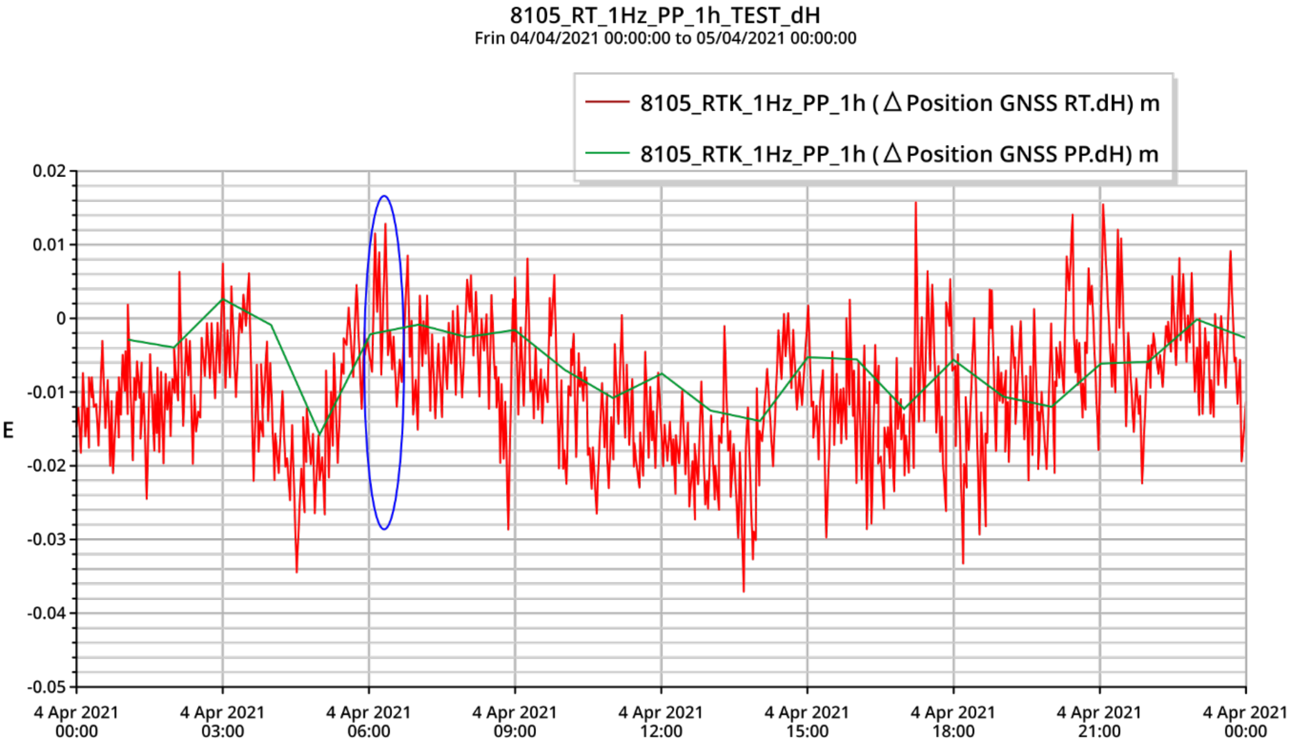


*Figure 7. The graph of the time series of height displacements (H) for point 8105 (04/04/2021) - solutions: 1 h (green), 1 sec (red). The moment of occurrence of the seismic event (blue).*

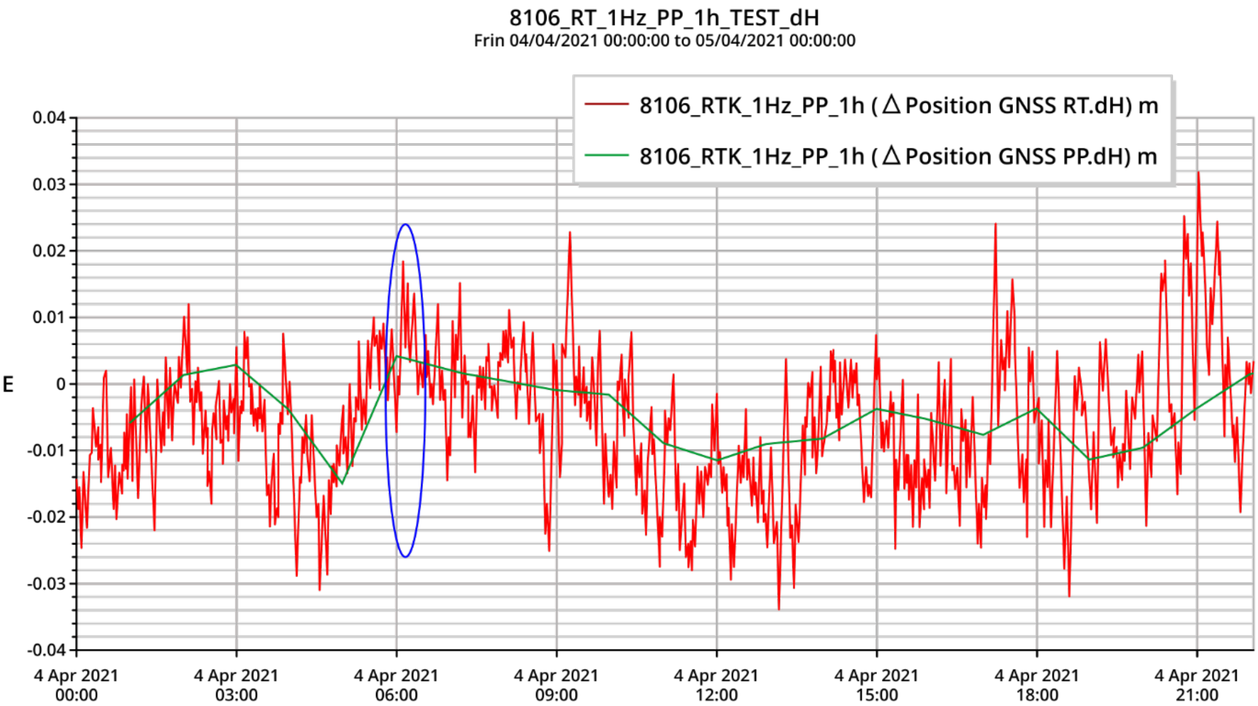


*Figure 8. Graph of the time series of height displacements (H) for point 8106 (04/04/2021) - solutions: 1 h (green), 1 sec (red). The moment of occurrence of the seismic event (blue).*

An increased increment of depression was found in the period related to the analysed seismic events (Figures 5 and 6). During this period, the monitoring station 8105 recorded an increase in subsidence by 4.2 mm, and at the 8106 station by 5 mm. The displacement change trend lines are marked in the figures. Basically, under the conditions of underground hard coal mining in the area of the Upper Silesian Coal Basin, in which the research area is located, the complete disappearance of surface subsidence due to the conducted exploitation is observed up to two years after its completion. Hence, the observed increments of subsidence should be considered significant. The increments were well beyond the accuracy of the method. However, before the occurrence of the phenomenon, disturbances in the course of recording were found (Figures 8 and 9). The observed velocity of displacement changes based on one-hour GNSS raw data solutions at point 8105 (Figure. 8) before the seismic event, i.e. from 00:00 a.m. and 3:00 a.m., was 2 mm/h. In the hours from 3:00 a.m. to 5:00 a.m., subsidence with the velocity of 8.5 mm/h was observed, and in the next time period, that is from 5:00 a.m. until the occurrence of the event, positive increments in displacements (uplifts) with the velocity of 14 mm/h were observed. Subsidence was observed at the velocity of 1.6 mm/h after the event. In the case of point 8016 (Figure. 9), a similar distribution of changes in displacements was observed. From midnight to 3:00 a.m. the velocity of the displacement changes was 2.8 mm/h, then, as in the first case, from 3:00 a.m. to 5:00 a.m., subsidence with the velocity of 8.2 mm/h was observed, and from 5:00 a.m. until the seismic event occurrence, uplifts were observed with the velocity of 18 mm/h. After the occurrence of the event, subsidence was observed at the velocity of 2.5 mm/h. The results were verified with the use of periodic geodetic, angular-line and levelling observations, which were carried out in the research area. Qualitative compliance with the results of observations at monitored points 8104 and 8105 was confirmed.

The results of the tests with regard to two seismic events recorded in the mining area of the Kazimierz-Juliusz mine, the detailed analysis of which are presented above, allowed for a preliminary connection of the observed surface movements with the occurrence of these events, in particular, with an increase of subsidence. The processes resulting from the equalisation of stress in the rock mass as well as hydrogeological processes had a potential impact on the occurrence of these phenomena. The movements of the groundwater table, which are an indicator of physical and mechanical processes in the rock mass, are observed both in the case of natural and mining seismicity before and after the phenomena. Hence, analyses of the observed surface movements are also planned, taking into account the results of measurements of the water level in the study area. In the remaining initially analysed periods, no significant changes were found in the observed values of surface deformation. These periods will be subject to further advanced statistical and numerical analyses over a longer period of time, over one year. Linear models and non-linear time series analyses will be used to reliably determine the dynamics of the occurring seismic phenomena, taking into account possible periodic systematic errors occurring in GNSS systems.

**CONCLUSIONS**

The proposed system of continuous monitoring of surface movements based on high-frequency and multi-system GNSS observations is an innovative solution, because it integrates geodetic measurements using many navigation systems with the module for data processing and visualisation of results in the study of land surface movements in seismically active post-mining areas. The proposed system uses the relative method to precisely determine the position, which today provides the most accurate way to determine coordinates from GNSS measurements.

The results of the analysis of observation of vertical displacements in relation to two seismic events recorded in the mining area of the Kazimierz-Juliusz mine allowed for a preliminary connection of the observed surface movements with the occurrence of these events. Significant changes in the values of vertical displacements on the monitored points were found.

The geomechanical condition for the seismic event to occur due to the destruction of the structure (activation) of the seismic events-producing layer is to achieve critical stress. The value of the critical stress is a function of the stress state and the strength parameters of the rock. Based on the analysis of deformation-strain states in the study area, it was concluded that during the period of a mine closure the probable cause of the event may have been complex processes occurring in the area of faults; in the case of the analysed events in the area of the Feliksowski and Będziński faults, resulting from the equalisation of stress in the rock mass as well as hydrogeological processes. In order to understand the mechanism of post-mining seismic phenomena, it is important to link the results of observation of surface movements with the results of measurements of the water table in the area of the study.

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