Application of the GNSS Method in the Monitoring of Mine Surface Displacement: A Systemic Review

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Abstract

Currently, Global Navigation Satellite System (GNSS) techniques are widely used for monitoring displacement. This study provides an overview of current developments in the application of GNSS technology for determining displacement based on the findings of 52 research publications over the past fifteen years, from 2009 to August 2024. The obtained results indicated that RTK-GNSS and PPP-GNSS are effective methods to monitor deformation, subsidence, and landslides in open-pit, underground, abandoned mines, and waste dumps. Besides, some limitations and benefits of this technology have been mentioned in this paper. Finally, the prospects of developing of GNSS technique combined with AI technology in displacement monitoring of mining areas were also presented. This paper offers a technical reference for expanding the understanding and knowledge of GNSS applications in detecting displacement in mining areas.

Keywords: *displacement, deformation, subsidence, landslide, mine area, GNSS*

1. Introduction

Surface deformations, also known as displacements, are a significant problem in mining due to their negative impact on the environment and construction sites. Since surface displacements are unavoidable, it's critical to keep an eye on the mining regions and their surroundings, which are equally vulnerable to the negative impacts of mining operations [1]. To date, there are many methods to detect deformations in mining areas including leveling, satellite radar interferometry, Global Navigation Satellite System (GNSS), aerial photogrammetry, and airborne LiDAR. Hybrid approaches are also employed, which combine two techniques, such as GNSS and InSAR or GNSS, and leveling, which are complimentary measurements done with a single methodology [1]. The data from conventional measuring methods are discontinuous and only exist in theory at the precise moment of observation, and thus involve a significant field workload. In order to achieve automatic and real-time monitoring, some scientists installed continuously operating GNSS equipment, transmitted the information gathered via a wireless network to a data processing station [2]. According to [3], the GNSS is currently among the most advanced technological tools available. With the emergence of modern satellite positioning systems, GNSS technology such as COMPASS, GPS, GLONASS, GALLIEO has been extensively utilized in spatial information science, military, transportation, and resource exploration [4]. Moreover, integrating InSAR and GNSS data for various applications has been the subject of intriguing papers published by numerous authors such as subsidence analysis [5], landslide back-analysis [6], ground deformation analysis [7], geology [8], etc. Indeed, [9] reviewed on application of GNSS technology for various purposes including atmospheric contribution evaluation and ground deformation identification. [10] provided a summary on the use of the GNSS method in geology and mining on the territory of Bulgaria. [1] conducted an overview of remote sensing and geodetic techniques (including GNSS) for identifying surface displacements induced by mining. Observations made with this technology have some benefits over those obtained with traditional ground approaches because of the high spatial and temporal resolution.

To date, there have been several reviews related to the determination of surface deformation due to mining. [11] provides a comparative discussion of various approaches used to evaluate mining-related subsidence. The obtained results revealed that in the last two decades, the main methods used for the detection and measurement of land subsidence occurrences including GIS and remote sensing, Light Detection and Ranging (LiDAR), and Differential Interferometric Synthetic Aperture Radar (DiNSAR). Similarly, based on a thorough analysis of a significant amount of scientific literature, [1] discussed surface displacement measurement techniques used in underground mining sites in relation to geodetic and remote sensing approaches. While [12] analyzed a large number of published research on mapping and assessing mining-induced subsidence using geographic information systems, [13] presented an overview of techniques for monitor, calculating, and simulating ground subsidence caused by coal mining. Also involved in the review of displacement determination methods, [14] supports the view that an effective and sufficiently precise method for tracking ground displacements brought on by mining-induced earthquakes is InSAR. Besides, from the perspective of subsidence management, recommendations, and methodologies are proposed to enhance the current mine stability evaluation methodologies

[15]. In addition, some reviews of the impact of mining-induced subsidence on the environment are also mentioned. Evaluation of the effects of aquifer system drainage and the spatial extent of ground displacement caused by mining was presented in [16]. In addition, an overview of the relative sea level increase induced by mining-caused displacement in the coastal areas [17]. Thus, although there are many assessments related to aspects of subsidence caused by mining, there is no study that has conducted an analysis of the application of GNSS technology in studying deformation in mining areas. So, in order to fill this gap, this study performs a comprehensive review of the use of the GNSS method in determining surface displacement due to mining. This movement can be horizontal or vertical or landslides in underground, open-pit, closed mines, or waste dump areas.

2. Material and methodology

A systemic review starts with identifying relevant main works and particular concepts, which are then operationalized into search terms and syntax. In this research, they are set up in the following search syntax for this study retrieval: ("Global Navigation Satellite System" OR "GNSS"; AND ("Deformation" OR "Subsidence" OR "Displacement" OR "Landslice"; AND ("Mine" OR "Mining" OR "Open pit mine" OR "Surface mine" OR "Underground mine" OR "Closed mine" OR "Abandoned mine" OR "Waste dump"). This search syntax is used to search systematically in databases of Google Scholar, ScienceDirect, Scopus, and Web of Science. English is the primary language used for searches. A comprehensive collection of scientific literature on many aspects of displacement investigation by GNSS techniques was found out. Book chapters, conference proceedings, and original papers published by international journals following peer review were collected. In January 2024, the data collection was conducted.

The obtained collection, which includes an initial list of 862 contributions, can be regarded as representative of the scholarly literature for the 15-year period 2009–2024 on the use of GNSS technology for displacement detection. The initial conclusion that can be made is that there is a significant amount of literature on the usage of the GNSS method for subsidence analysis, but no study in the world has performed a comprehensive assessment. The abstracts and titles of the research were checked to evaluate whether they agree with the content of this review. Certain study kinds are excluded, including reports and industry trade papers. After a process of screening to remove duplicate entries, documents are sent forward for suitability assessment. Finally, our systematic review of the literature is based on 66 papers in total.

3. Application of GNSS technology in monitoring of mine surface displacement

Mining operations have the potential to deform the surface and harm the ecosystem [18]. Surface deformation from underground mining has a negative impact on locals' quality of life and personal safety. It also creates obstacles to the safe and effective extraction of subsurface resources [19]. According to [20] there are several ways to measure ground deformations, including leveling, laser scanning, synthetic aperture radar, satellite navigation systems, and many more. These days, with the advancement of GNSS technology, mining deformation monitoring technology has become more innovative. The usage of GNSS systems in resource exploration has increased significantly since the emergence of modern satellite positioning systems [21]. Similarly, as the conclusion of the study [22] indicates, at surface lignite mines, several techniques have been developed for detecting ground deformation such as total stations, GNSS, laser scanners, photogrammetry, ground-based radar, drone, etc. For the GNSS approach, they concluded that the precision of this method is adequate for observing ground deformation, even with RTK. Therefore, up to now, many publications have mentioned monitoring surface deformation due to mining using GNSS technology. According to [23], for two decades, the use of global navigation satellite system (GNSS) measurements to monitor deformations induced by underground mining activity has been a global standard. These monitoring techniques combine epoch measurements with one of the following methods: the rapid-static method with double difference (DD) phase observations, the static precise point positioning (PPP) method, the real-time kinematic (RTK) method and PPP, and a postprocessing (P-P) method.

3.1 RTK monitoring technique

3.1.1 Application of GNSS technology in monitoring of deformation in mining areas

As seen in Eq. (1), RTK uses the Double Difference (DD) model to remove the majority of observational errors, leaving just the coordinate and ambiguity parameters to be estimated in a brief baseline [24].

$$\begin{aligned} p_{rb,k}^{ij} &= \rho_{rb}^{ij} + e_{rb,k}^{ij} \\ L_{rb,k}^{ij} &= \rho_{rb}^{ij} + \lambda_k * N_{rb,k}^{ij} + \epsilon_{rb,k}^{ij} \end{aligned} \quad (1)$$

where P and L are the code and phase observations (m), respectively; i and j stand for the non-reference and reference satellites, respectively, and r and b for the rover and reference stations, respectively; N is the integer ambiguity in cycles; ρ is the geometric distance (in meters) between the satellite and the receiver; k is the signal frequency; k is the wavelength of the k-th signal frequency; e and ‿ are the sum of the measurement error, multipath error, and residual model error for the code and phase observations, respectively [24].

RTK method has been widely utilized in monitoring deformation in mining areas. The GPS RTK method has been applied in subsidence monitoring since the early years of the last decade. In order to meet surface deformation monitoring's precise requirements, [25] proposed a new GPS RTK surveying technique that uses rod measurement. This technique can lessen the influence of multipath error in the U direction, effectively prevent the impacts of vertical deviation and shaking error of the surveying rod, and further increase positioning precision. Similarly, the GPS RTK approach was adopted to enhance the precision and dependability of mine surface subsidence monitoring. Subsequently, the mechanism responsible for the primary systematic mistakes was examined, drawing on several theories and techniques. The accuracy of estimations can be increased by using this method, which can completely remove the inevitable shaking mistake, vertical deflection, and, to some extent, lessen the multipath effect [26].

In this research [20], based on GNSS technology, the findings of two years of ground deformation monitoring in

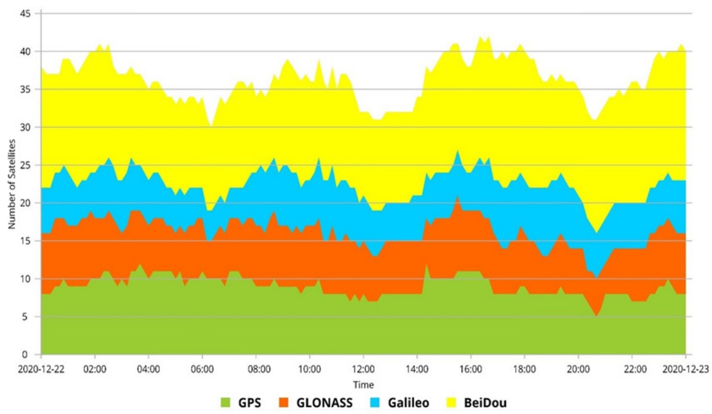

Fig. 1. Number of GNSS satellites visible above the observation location
Rys. 1. Liczba satelitów GNSS widocznych nad miejscem obserwacji

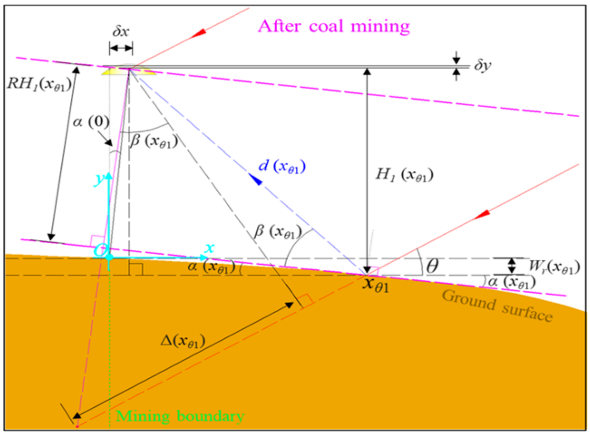

Fig. 2. Reflection model for subsided ground surface caused by underground coal mining [39]
Rys. 2. Model odbicia dla osiadającej powierzchni gruntu spowodowanej podziemną eksploatacją węgla [39]

coal mining regions in Upper Silesia, Poland are presented. Real-time (RT) and near real-time (NRT) GNSS techniques were used to verify the long-term subsidence events, and they were cross-referenced with a daily postprocessing solution. Besides, [27] provided the processing procedure and findings from their analysis of the earth surface displacement data observations during coal mining at the Kostenko mine of the Coal Department of ArcelorMittal Temirtau JSC, Karaganda Coal Basin using the GNSS methods. The obtained results show that the proposed method of observing the displacement of the earth's surface is more economically advantageous and requires significantly less time compared to measurements made using traditional expensive geodetic methods. According to [4], in order to establish real-time and quasi-real-time deformation monitoring methods, the GNSS Continuously Operating Reference Station (CORS) offers services for navigation on the basis of pseudorange measurements and provides carrier phase information. Therefore, in light of mining technology for CORS, They suggested a large-area 3D deformation monitoring system for mining areas. The results showed that the proposed GNSS-RTK can improve the temporal and spatial resolution of the monitoring of mine deformation. In another study, it has proven possible to evaluate displacements both vertically and horizontally with great precision using geodetic networks. The latter is made up of inclinometers and GPS networks to facilitate the detection of horizontal motions, while the former is capable of estimating values of subsidence (e.g., geodetic high-precision leveling systems). This study presented the results and remarks on the usage of a GPS geodetic network for continuous surface deformation monitoring in waste dumps of the Bages region of Catalonia (Spain) [28]. In addition to, utilizing GNSS satellite receivers and robotic total stations to monitor open pit mines is presented in [29]. This study demonstrated the combination of robotic total station equipment and GNSS receivers to provide a completely automated, accurate, efficient, and economical survey monitoring system for large open pit mines. In the study [30], large-scale mobility in the mining area can be detected using continuous-time or GNSS location time series with high sample rates. Therefore, they presented a GPS method for monitoring seismic events and surface displacement that occurs during mining-induced tremors.

Beyond its use for monitoring deformation in surface or underground mines, this technology was applied in closed mines. According to [31], during the time of mine closures, the issue of monitoring surface ground movements in post-mining sites is very crucial. Therefore, the study uses the GNSS to continuously monitor surface movements at the abandoned hard coal mine "Kazimierz-Juliusz" in Poland. Based on the results acquired, it was determined that the best way to meet the needs of ongoing geodetic monitoring in the research region was to conduct GNSS measurements using three navigation systems: GPS, GLONASS, and Galileo. Figure 1 shows the quantity of GNSS satellites that can be seen above the observing site.

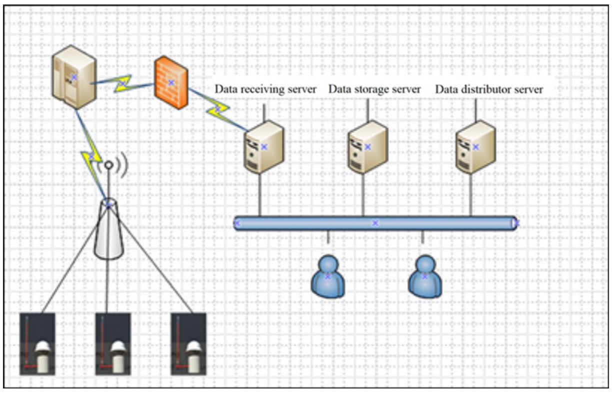

Fig. 3. Schematic diagram of automatic monitoring system [45]
Rys. 3. Schemat ideowy automatycznego systemu monitorowania [45]

In addition to predicting the mining-caused deformation, the GNSS system was also utilized to validate the precision of the displacements determined by InSAR-based methods. According to [32], to fully understand the rule of mining subsidence and to set safe production and construction guidelines for mining areas, it is necessary to measure the surface three-dimensional deformation fields accurately in a mined-out region. Thus, they suggested a better fusion technique to monitor this three-dimensional displacement based on the GNSS and InSAR measurements. This technique can be used to acquire three-dimensional deformation fields, which can then be used as a foundation for safe production in nearby mining sites. In the [33], During the SAR acquisition period, the GPS1 and GPS2 stations were situated in locations that were significantly and insignificantly impacted by underground mining operations, respectively. Similarly, the precision of the DinSAR deformation maps was validated using the GNSS data in [34]. Based on data gathered from the ground network of permanent stations, the GNSS monitoring of ground surface displacements has been carried out. In addition, GNSS data were applied to compare with the results of monitoring ground motion occurrences caused by underground mining operations in Poland based on the interferometric synthetic aperture radar method [35]. The same purpose of assessing accuracy, [36] used the GNSS static monitoring network system situated close to the mining area at the southwest foot of the mountain to determine three-dimensional ground surface displacement data. The findings revealed that there is good agreement between the estimated value identified by InSAR and the displacements measured by GNSS. Another study [37] also used InSAR and GPS measurements to monitor and analyze deformation in the Kunyang phosphate mine fusion. The findings of this study provide a scientific foundation for the management and prevention of landslides, collapses, and other undiscovered geological hazard risks brought on by the mining activities carried out in the Kunyang Phosphorus Mine. Also using this method, [38] introduced an integration process that takes into account the strengths and weaknesses of GNSS and Differential Interferometry SAR (DInSAR) monitoring approaches to monitor deformation in the Upper Silesian coal mining region (southern Poland). Besides, in order to determine the ground surface deformation of underground coal mining, [39] suggested the GNSS approach interferometric reflectometry (GNSS-IR). The GNSS reflection model for the subsided ground surface induced by underground coal mining is illustrated in Figure 2. The results of this study indicate that the navigational GNSS instrument may be considered to be a novel kind of sensor for continuously and economically detecting surface displacement.

Furthermore, the accuracy of the GNSS method is also mentioned in some studies. In the [40], the duration of GPS in ground deformation measurements in mining areas was determined. The results show that a GPS session should last at least twelve hours in order to attain sub-cm precision of height coordinate at a 95% confidence level in a single observation session. Moreover, [41] conducted a study on monitoring local deformation using GNSS in an open pit mine to to solve the issue of how to obtain millimeter accuracy while determining displacements with GPS.

According to [42], high-accuracy geodetic surveys are necessary to determine the deformation indices in areas affected by open pit mines. This allows for the identification of potential dangers. Thus, They discussed the fundamentals of precisely determining three-dimensional displacements using GPS technology. The obtained results indicate that the 3-D coordinates of the observed points can be accurately determined to within 2-3 mm.

3.1.2 Application GNSS technology in monitoring of ground subsidence in mining areas

In addition to determining deformation caused by mining, GNSS methods are also used for monitoring ground subsidence in mining areas. According to [43], in coal-mining regions, the amplitude of ground subsidence can reach up to 10 cm per day and occurs continuously. Thus, timely and accurate monitoring of ground subsidence is essential to ensure the safety of coal-mining regions. This study provides a real-time ground subsidence monitoring system that operates constantly on the Global Navigation Satellite System. Unlike the traditional leveling surveying approach, the suggested method can match the precision requirement of ground subsidence monitoring and offer continuous subsidence information in real-time. In the study [44], to precisely observe large-area mining subsidence, a high-precision GNSS monitoring system was constructed using the neighboring international GNSS service (IGS) stations as reference points. The suggested theory was used to monitor mining subsidence in China's northern Anhui coal mine. The findings revealed that the accuracy

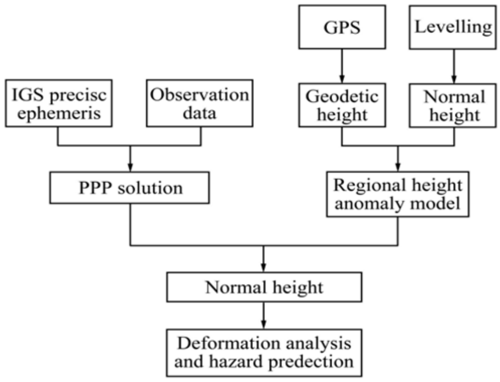

Fig. 4. Vertical subsidence monitoring based on PPP [44]
Rys. 4. Monitorowanie osiadania pionowego w oparciu o PPP [44]

of deformation can reach the millimeter level with four hours of observation. In mining subsidence research, [45] offers a novel technological method for analyzing the law of surface movement. They used time series DInSAR technology in conjunction with a number of GNSS monitoring stations to determine precise, dependable, and fine mining deformation results. Figure 3 shows the automatic monitoring and data distributor system. The findings of the study can offer a solid scientific foundation for computing mining subsidence, evaluating the damage to buildings or structures, evaluating land damage, and supporting environmental control initiatives. To comprehensively evaluate subsidence in mining, [46] presented a weighted total least-squares approach that can be utilized to find the piecewise linear mapping between D-InSAR data and GNSS data. This mapping can be used to improve the findings of traditional D-InSAR monitoring, especially in locations with significant gradient subsidence. In the event of large-gradient subsidence, it is discovered that the improved data is more accurate and dependable than the traditional D-InSAR monitoring data. Additionally, to save expenses and improve security, there is ongoing research into ways to monitor mine subsidence better. As a result, the applicability of numerous novel techniques and equipment is evaluated. UAV, and GNSS are considered a promising method for gathering large amounts of data quickly. Thus, [47] conducted a study to detect mine subsidence using this proposed approach. Overall, the results indicate that UAV photogrammetry and GNSS RTK are both appropriate for monitoring mine subsidence.

3.1.3 Application RTK-GNSS technology in monitoring of landslides in mining areas

[48] described the implementation of a geodetic deformation monitoring method on two significantly damaged and unexplored research locations in India including Bhurkunda coal mines in Jharkhand, and the Sirobagarh landslide in Rudraprayag, Uttarakhand. For the Bhurkunda site (marked by subsidence owing to underground coal mining), A network of 56 GNSS points, densified using Total Station (TS) ground points, was established during three field trips. In order to monitor the recurrent landslides in Sirobagarh caused by the local geology and rainfall, a GNSS network including six control sites was set up over a 500 x 600 m^2 region. According to [49], monitoring landslides caused by waste dumps can be done in a variety of ways these days using GPS, total stations, remote sensing, UAVs, lidar, and other technologies. However, these technologies can only monitor periodically, not continuously in real-time. Therefore, It was decided to use GNSS CORS technology for the design and construction of a real-time waste dump landslide monitoring system. This device gives immediate warning in the event of a landslide and enables continuous real-time monitoring. Additionally, it has the benefit of being inexpensive, adaptable, and simple to install for monitoring stations.

3.2 PPP monitoring technique

According to [24], PPP-GNSS measurement technology is able to make up for RTK's disadvantages in terms of receiver configuration, cost, and range when compared to RTK. Several studies have demonstrated that displacement monitoring can be done using this method. Four continuous operation reference station (CORS) stations in the mining region were used to study the displacement status, and the viability of employing PPP in mining area deformation determination was confirmed in the study [50]. Besides, PPP technology and its application for monitoring mining deformation was presented in [51]. Figure 5 shows the procedure of vertical subsidence determining based on PPP. The obtained results showed that when PPP is employed, multiple quality metrics demonstrate that the precision of deformation monitoring can reach the cm and even mm levels.

In another study [45] found that, by using only one receiver, precise point placement (PPP) eliminates issues brought on by base station limitations when using existing techniques like real-time kinematics. Therefore, they suggested a novel approach to monitor deformation in the mine area through PPP. The results of the monitoring experiment demonstrate that, utilizing this method, the monitoring index of the series under various intervals could be, on average, 1-2 mm, which is significantly better than the original monitoring sequence. As a result, every result demonstrated the method's viability and validity. In the view of [46], the surface of the mining area is prone to disasters including cracking, shifting, and collapse, which can seriously harm the local ecology and human population. Thus, based on the PPP technique, an adaptive filtering algorithm is proposed for deformation monitoring in mining areas. Simultaneously, the actual tests are conducted using the data gathered from the mining engineering practice, and the algorithm's superiority is subsequently confirmed.

With GNSS RTK, landslide deformation in mining area can be precisely observed. But unstable locations can cause reference stations to shift, producing inaccurate data. Thus, [47] suggested a procedure that employs the PPP methodology to identify the reference station's instability and then adjust for the movement of monitoring stations. The results indicated that the suggested method provides reliable and accurate monitoring data, enabling accurate forecasting and early warning systems in the deformation region.

4. Discussion and future perspective

The literature shows that the GNSS technology for monitoring mining-induced subsidence has the advantages of high observing precision, a quick and adaptable network structure and widespread use [48]. Even with their drawbacks, such as inefficiency and a high field workload, they will remain essential for monitoring subsidence in the near future. The experiment results indicate that RTK can be widely employed in small-scale displacement monitoring because it is able to rapidly and precisely acquire positioning information with millimeter-level accuracy. However, it is dependent on a reference station, which is somewhat costly, and is unable to independently establish absolute coordinates [24]. In addition, for monitoring landslides in mining areas, RTK appears to have the fastest reaction time and is typically used to record the abrupt deformation of landslides in real-time. In contrast, because PPP takes a long time to converge and produce high-precision absolute coordinates, it is commonly employed to regularly verify the stability of reference stations [24]. On the other hand, in studying landslides, although PPP can provide absolute coordinates directly without the need for a reference station, its accuracy can only be attained to the centimeter level after tens of minutes, making it suitable for monitoring landslides that vary slowly and occur close to real-time [24].

In addition, previous studies have shown that numerous studies were gathered to confirm the potential application of artificial intelligence (AI) algorithms in the GNSS domain. Deep learning (DL) and machine learning (ML) are the two methods available for achieving intelligence. The two most popular AI methods utilized in the literature to improve GNSS system location accuracy are Support Vector Machine (SVM) and Convolutional Neural Network (CNN) [49]. Although there has not been much research on this application, the deep self-attention neural network approach may be a potent substitute for GNSS coordinate time series prediction, and it will have extensive applications in the domains of early warning for deformation and reference frame maintenance [50]. On the other hand, in the last several years, artificial intelligence (AI) has been used to tackle a number of issues with GNSS, such as accurate location, navigation in challenging environments, and interference cancellation and mitigation [51]. Furthermore, combining machine learning and GNSS technology in determining deformation is not required to 1) preinterpolate GNSS point displacements, and 2) predict GNSS and InSAR point-by-point variance components [52]. With the above analytical advantages, applying AI and GNSS in subsidence monitoring will be effective and highly accurate. However, this proposed method has not been applied in mining areas. Therefore, in the future, scientists need to research to include this method in studies to determine deformation due to mining.

5. Conclusion

This study discusses the utilization of GNSS techniques for monitoring displacement induced by mining based on publications from the last 15 years. The review conducted an analysis 52 papers related to movement monitoring in mining areas by the GNSS method that had been published in scientific journals and M.Sc./Ph.D. theses. The obtained results showed that RTK-GNSS and PPP-GNSS technology can be performed to determine surface deformation, subsidence, landslides in underground, surface, closed mines, and waste dumps. As proven in this paper, although there are some limitations such as inefficiencies and large workloads in the field, GNSS is still necessary to monitor displacement in the near future. In addition, the findings have revealed that RTK in displacement monitoring can quickly obtain monitoring results with millimeter accuracy in stable and reliable reference stations, but its range of services is limited. Moreover, the PPP offers the advantages of not requiring a reference station, cost-effectiveness, and absolute coordinates, which are directly applicable to displacement observing in a vast range, slow-variable, and near real-time, even if it takes tens of minutes to reach steady centimeter-level monitoring precision. On the other hand, the paper also indicated that with many advantages of the combination of GNSS and AI technology, this approach promises to bring many useful applications for monitoring displacement in mine areas.

Conflicts of Interest

The authors declare no conflict of interest.

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Zastosowanie metody GNSS w monitorowaniu przemieszczeń powierzchni kopalni: przegląd systemowy

Obecnie do monitorowania przemieszczeń powszechnie stosuje się techniki Globalnego Systemu Nawigacji Satelitarnej (GNSS). Niniejsza praca stanowi przegląd aktualnego rozwoju zastosowań technologii GNSS do wyznaczania przemieszczeń na podstawie wniosków z 50 publikacji naukowych z ostatnich piętnastu lat, od 2009 r. do sierpnia 2024 r. Uzyskane wyniki wskazują, że RTK-GNSS i PPP-GNSS są skuteczne metody monitorowania deformacji, osiadań i osuwisk w kopalniach odkrywkowych, podziemnych, opuszczonych kopalniach i na składowiskach odpadów. Poza tym w artykule wspomniano o pewnych ograniczeniach i zaletach tej technologii. Na koniec przedstawiono także perspektywy rozwoju techniki GNSS w połączeniu z technologią AI w monitorowaniu przemieszczeń obszarów górniczych. W artykule przedstawiono odniesienia techniczne umożliwiające poszerzenie zrozumienia i wiedzy na temat zastosowań GNSS w wykrywaniu przemieszczeń na obszarach górniczych.

Słowa kluczowe: *przemieszczenie, deformacja, osiadanie, osuwisko, teren kopalni, GNSS*