The suitability of advanced geospatial technologies in monitoring mine surface displacement

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Abstract

This study conducts a thorough review of the current scientific literature on the application of geospatial methods in the assessment of mining-induced displacement. The scope of research included technologies for determining deformation, subsidence, and landslide in mining areas. Global Navigation Satellite Systems, Unmanned Aerial Vehicles, Terrestrial Laser Scanners, Remote Sensing, and fusion methods are approaches used to solve the research objectives. Additionally, the paper also mentions some advantages, disadvantages, and scope of application of these methods. The investigation revealed that the displacement detection method most commonly used at the moment is satellite radar interferometry.

Keywords: Geospatial technology, Global navigation satellite system, Unmanned aerial vehicle, Terrestrial laser scanners, Remote sensing, Displacement, Mining

1. Introduction

Although most mineral exploration in the past was done by hand, the procedure has since shown to be costly, time-consuming, and error-prone, which has led to investment losses [1]. Thus, scientists and researchers have developed new techniques that help lower mining hazards, increase production efficiency, and lower operating costs to prevent such negative effects. Geospatial technology is one of these inventions. Rapid advancements in geospatial technology have made it broadly applicable for a variety of geographic location-related applications. Geospatial technology is being used for many different purposes these days [2]. According to Riecken [3], approximately 80% of all choices made by the public sector are dependent on geo-referenced data, and 80% of current information has a spatial or geographic component. Geospatial data is not only used in geography but also in other fields such as land use planning [2], disaster risk management [4], land degradation assessment [5], mapping [6], environmental influence assessment [7], military [8], mining [9], etc. In particular, in the mining industry, this technology can be applied in mine design, reserve estimation, material handling optimization, mineral exploration, safety management, etc. [1]. According to statistics on Science Direct with the keywords "geospatial technologies" or "geospatial technologies in mining", the number of studies using this technology for all fields and in the mining industry has increased significantly from 2014 to the present (Tab. 1). In addition, if calculated by percentage, it shows that geospatial technology is comparatively prevalent in the mining industry (accounting for 17−21.7%). This proves that using geospatial data is becoming increasingly popular in many applications, especially in the mining sector.

Up to now, there are some reviews on the uses of this technology. While Acharya & Lee [10] presented a review of applications using remote sensing and

Received 17 September 2024; revised 18 December 2024; accepted 20 December 2024.
Available online ■ ■ ■

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https://doi.org/10.46873/2300-3960.1472

Tab. 1. A number of studies that used geospatial technologies for all fields and in the mining industry.

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
All fields	661	922	1101	1235	1353	1743	2176	2725	3089	3480	5134
Mining	125	177	187	254	265	383	451	581	672	683	1059
industry	18.9%	19.2%	17%	20.6%	19.5%	21.9%	20.7%	21.3%	21.7%	19.6%	20.6%

geospatial technologies for sustainable development, Pérez Hoyos et al. [11] reviewed developments in the use of geographic technology for the detection and assessment of ecosystems that depend on groundwater, Ahansal et al. [12] conducted an overview of the literature on machine learning and geospatial technology applied to water resource management. Besides, Kaur et al. [13] conducted a review to emphasize how improvements in geospatial technology have made it possible to evaluate soil properties' spatial variability at the regional level using satellite data. In addition to assessing the potential and use of geospatial techniques in the field of geotechnical engineering [14], the difficulties and opportunities of using this method to improve marine spatial planning were reviewed in the study [15].

In the mining industry, Said et al. [1] discussed into detail on how geospatial technology is used in safety enforcement, material handling optimization, mine design, reserve estimation, and mineral exploration Additionally, some scientists have reviewed the applications of specific geospatial technologies in the mining sector. A typical example is a study by Dang and Nguyen [16], where the author analyzed the potential applications of unmanned aerial vehicles (UAV) in the mining field. In another research, Ang et al. [17] performed a comprehensive analysis of remote sensing and GIS applications to evaluate the socioeconomic effects of mining. Furthermore, in order to increase awareness and understanding of UAV applications for surveying and mapping in mine regions, Nguyen et al. [18] offers a technical reference. In addition to using UAVs, the possibilities of Geographic Information Systems (GIS) and remote sensing methods for assessing the performance of reclamation efforts in areas damaged by coal mines were mentioned in Karan et al. [19]. Although many studies have reviewed the overall application of geospatial technology in the mining sector, most studies have focused on evaluating specific applications based on one technology, such as UAV, TLS or remote sensing. In fact, there has not been a comprehensive review analyzing the applications of mining site displacement assessment using all advanced technologies such as UAV, Global Navigation Satellite System (GSNN), Terrestrial Laser Scanner (TLS), and remote sensing data in the assessment. Therefore, to fill this gap, this paper conducts an overview of the application of geospatial technology in determining displacement in mining regions.

2. Methodology

The studied methodology used in the paper consists of four following steps:

a. Gather databases: The literature was collected from a few databases, including Science Direct, Web of Science, Scopus, and Google Scholar.
b. Filter databases: Use the keywords, title, abstract, and terms "Geospatial Technology" OR "GNSS" OR "GPS" OR "Remote sensing" OR "UAV/Unmanned Aerial Vehicle/Drone" OR "TLS" OR "Terrestrial Laser Scanning" and "Mine Surface Displacement/Subsidence/Deformation" to filter the databases. In addition, the publication time should also be considered when searching for data. This study only considered publications from 2010 to 2024.
c. Read the document: Check the paper's relevance by reading it.
d. Sort papers: Document classification based on applying advanced geospatial technology in monitoring mine surface displacement. The publications are categorized into distinct purposes, with each paper being assigned to a single category.

As seen in Figure 1, we used PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), a systematic article selection approach, to document this process [20]. The search results revealed 100 articles relevant to the review topic published in English after 2010.

3. The role of geospatial data in monitoring displacement in mining areas

The different geospatial data kinds that are frequently used in monitoring displacement in mining areas, including LST, UAV, GNSS, remote sensing, and combinations of these formats.

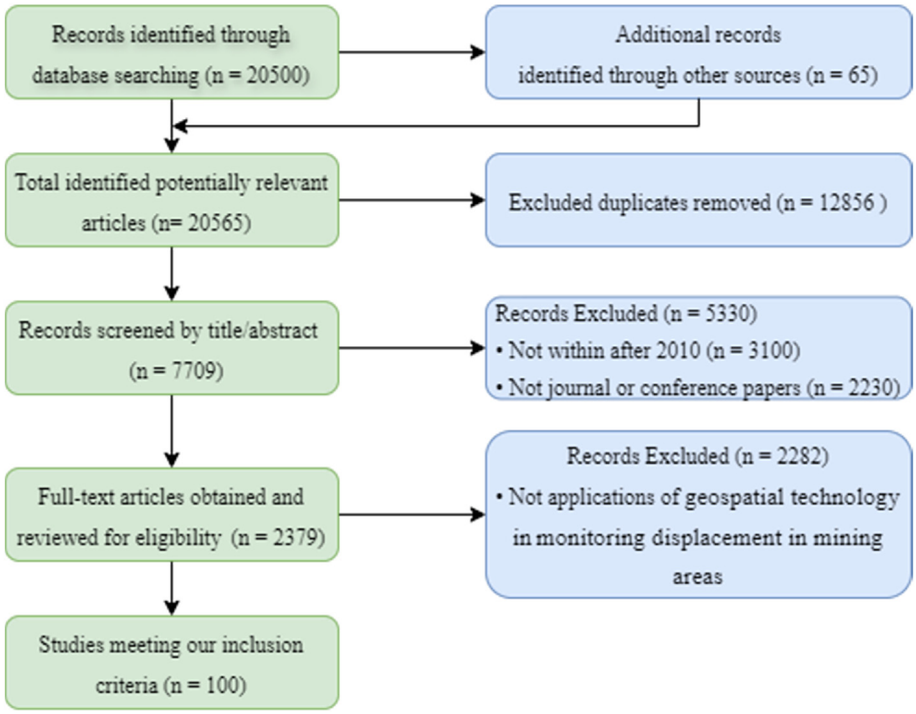

Fig. 1. PRISMA flowchart of paper screening.

3.1. Monitoring displacement in mining areas via GNSS technology

Since the development of contemporary satellite positioning systems, the application of GNSS systems in resource exploration has grown dramatically [21]. According to Prokos & Roumpos [22], the accuracy of the GNSS approach is sufficient to observe ground deformation, even with RTK. Thus, surface deformation caused by mining has been investigated using GNSS technology in numerous publications up to this day. The utilization of GNSS measurements for monitoring deformations caused by underground mining activity has been a worldwide standard for two decades [23]. These techniques for monitoring integrate epoch observations with one of the following approaches: the static precise point positioning (PPP), the real-time kinematic (RTK) and PPP, the rapid-static with double difference (DD) phase observations, and a post-processing (P-P) method.

3.1.1. RTK monitoring technique

3.1.1.1. GNSS technology in monitoring deformation in mining areas. Monitoring subsidence has been done with the GPS RTK approach since the beginning of the past decade. A new GPS RTK surveying method utilizing rod measurement was presented by Liu et al. [24] in order to satisfy the exacting requirements of surface deformation monitoring. This method can further improve positioning accuracy and successfully mitigate the effects of vertical variation. Similar to this, the GPS RTK method was used in the study to improve the precision and consistency of surface deformation detection in mines [25]. This technique can minimize the multipath impact to some extent and eliminate the unavoidable shaking error and vertical deflection. In another study Tondaś et al. [26], the long-term subsidence occurrences were confirmed using real-time (RT) and near real-time (NRT) GNSS techniques, which were cross-referenced with a daily post-processing method. From that, ground deformation in coal mining regions in Upper Silesia, Poland, was determined. Moreover, according to Issabek et al. [27], compared to expensive geodetic methods, the GNSS approach to monitoring the displacement of the earth's surface is much faster and more cost-effective. This was demonstrated in their research, which revealed the processing method and results from their examination of the ground surface displacement data observations made during coal mining at the ArcelorMittal Temirtau JSC coal department's Kostenko mine. Also related to using GNSS technology in monitoring the deformation of mining areas, Jing-Xiang & Hong [21] recommended a large-area 3D deformation monitoring system for mining sites based on technology for CORS. The findings demonstrated that the suggested GNSS-RTK can enhance the monitoring of mine deformation's temporal and geographical resolution. In another work, Costantino & Angelini [28] highlighted the findings and observations on the application of a GPS geodetic network for ongoing surface deformation monitoring at the trash dumps located in the Bages district of Catalonia, Spain. The results obtained show that it is possible to use geodetic networks to analyze displacements both vertically and horizontally with high precision. In addition, continuous-time or GNSS position time series with high sample rates can be used to identify large-scale mobility in the mining region. Therefore, Szczerbowski & Jura [29] illustrated how to use GPS to track seismic activity and surface displacement brought on by mining-related tremors.

Furthermore, it is important to monitor surface ground movements at post-mining sites during the period of mine closures. However, not many scientists have used this technology to monitor the deformation of closed mines. At the closed hard coal mine "Kazimierz-Juliusz" in Poland, Sokoła-Szewioła & Siejka [30] constantly tracks surface movements using GNSS. The findings revealed that conducting GNSS measurements using the three navigation systems – GPS, GLONASS, and Galileo – was the most effective approach to satisfy the requirements of continuous geodetic monitoring in the research zone.

According to Pham et al. [31], in order to identify the displacement index in regions impacted by open pit mines, highly precise geodetic surveys are required. They presented the principles of using GPS technology to precisely calculate displacements in three dimensions. The results show that it is possible to precisely measure the 3-D coordinates of the detected points to approximately 2–3 mm.

3.1.1.2. GNSS technology in monitoring ground subsidence in mining areas. GNSS techniques are utilized not just to detect mining-related deformation but also to track ground subsidence in mining locations. In contrast to the traditional methods, the proposed solution can provide continuous subsidence information in real time and fulfill the precise requirement of ground subsidence monitoring. According to Hu et al. [32], it is necessary to precisely and quickly monitor ground subsidence to keep coal-mining sites safe. Thus, using the Global Navigation Satellite System, this study offers a continuous real-time ground subsidence monitoring system. Also used this technology, using the international GNSS service stations as reference points, a high-precision GNSS monitoring system was built in the study Xu et al. [33] to accurately monitor large-area mining subsidence. The results showed that after 4 h of observation, the accuracy of deformation could be measured at the millimeter level.

3.1.1.3. GNSS technology in monitoring landslides in mining areas. According to Jagiwala & Shah [34], there are numerous methods available nowadays to monitor landslides resulting from waste dumps, including GPS, lidar, UAVs, remote sensing, and other technologies. These technologies can't, however, monitor continually or in real-time; they can only do it periodically. Thus, it was decided to build a real-time waste dump landslide monitoring system using GNSS CORS technology. Not only does this device provide timely warning in case of landslides and allow continuous real-time tracking, but it also has the advantage of being affordable, flexible, and easy to set up for monitoring stations. Also involved in landslide research, Lian et al. [35] detailed the application of a geodetic deformation monitoring approach on two severely damaged and undiscovered study locations in India, including the Sirobagarh landslide in Rudraprayag, Uttarakhand, and the Bhurkunda coal mines in Jharkhand. For the former site (Bhurkunda), a densely populated network of 56 GNSS stations using Total Station ground points was created throughout three field excursions. For the latter location, a GNSS network, including six control sites, was set up over a 500×600 m^2 zone to monitor the frequent landslides in Sirobagarh that are caused by the local geology and rainfall.

3.1.2. PPP monitoring technique

According to Huang et al. [36], the drawbacks of RTK in terms of receiver design, cost, and range can be addressed by using PPP-GNSS measuring technology. Numerous studies have shown that this approach can be used for displacement monitoring. In the study Jiang et al. [37], the displacement status was investigated using four continuous operation reference station (CORS) stations in the mining zone. The obtained results proved the feasibility of using PPP in mining area deformation detection. Similarly, Mosavi et al. [38] proposed PPP technology and its use in monitoring mining subsidence. The findings demonstrated that the precision of deformation monitoring can reach the cm and even mm levels when PPP is used. Also related to using the PPP method in identifying movements in the mining region, Li et al. [39] discovered that precise point placement (PPP), which employs a single receiver, resolves problems caused by base station restrictions when utilizing current methods like real-time kinematics. The findings of the monitoring experiment show that this method can be used to improve the monitoring index of the series under different intervals by an average of 1–2 mm compared to the original monitoring sequence.

3.2. Monitoring displacement in mining areas via terrestrial laser scanning

The terrestrial laser scanner, which allows for data gathering with previously unheard-of precision and accuracy, is a breakthrough in the collection of spatial information data [40]. Thanks to its accuracy, consistency, and efficiency, TLS technology is now an effective tool for many applications, of which displacement tracking in mining areas is one of the popular applications.

3.2.1. Terrestrial laser scanning technology in monitoring deformation in mining areas

Detecting surface geometry variations among building objects located inside underground mining exploitation areas is essential for maintaining the security of mining operations. Matwij et al. [41] developed a semi-automated method for figuring out the displacement field for regions impacted by underground mining using multi-temporal TLS point clouds. When compared to the displacement vectors obtained in the previously mentioned articles, the proposed approach yields much higher precision. In another study, Lipecki and Huong [40] also discussed the method for TLS and the transportable terrestrial laser scanning system, which have been utilized to detect the geometric displacement of vertical shaft sections at many vertical shafts in Polish mines. Besides, potential uses of TLS technology for engineering object monitoring have been discussed in Skoczylas et al. [42]. A thorough spatial documentation of an object impacted by an ongoing mining activity is made possible by this technology. The results of the analysis showed that there was object deformation as well as changes in the orientation of the trestle bridge concerning the mined coal wall.

In addition to using in underground mines, TLS is also a popular method to identify displacement in surface mines. Wang et al. [43] provided an automated method for extracting building deformation in mining locations based on the TLS point cloud. The deformation values obtained by this method and the manual method were almost comparable, with an absolute error of less than 8 mm. The recommended method outperformed the manual extraction method in terms of stability. In the study of Kukutsch et al. [44], this technique was applied in situ at the selected mining location in the Czech portion of the Upper Silesian Coal Basin in order to confirm the changes in space (movements and deformations) of mining activities. Monitoring the displacement of the road before it approaches the longwall face on the selected tailgate was the main purpose of 3D laser scanning at Lazy Mine. In addition, Van der Merwe & Andersen [45] evaluated the efficiency of a stop-and-go laser scanning method in the mine shaft to determine the exact position, angle, and deviation of the bunton plates at Thembelani Mine. The obtained results indicated that laser scanning offers many benefits when ongoing data analysis is required. A multitude of departments and teams can continue working on a variety of applications using the vast laser scan datasets off-site, such as planning, design, engineering, safety, geology, and rock engineering.

3.2.2. Terrestrial laser scanning technology in monitoring ground subsidence in mining areas

According to Bing et al. [46], information about the entire subsidence area is not always retrievable using traditional data-collecting procedures. Thus, the primary goal of this work is to recreate a digital elevation model using point cloud data from TLS. The findings reveal that a DEM built using TLS point cloud data can get a high enough level of precision. Besides, there are many limitations when using traditional methods to detect subsidence in mining areas. To address the shortcomings of the conventional approaches, Gu et al. [47] provides a TLS-based subsidence monitoring strategy without a goal in the mining region. This method reduces labor effort, transfers the main duty to the internal industry, and streamlines the field measuring procedure. The findings revealed that in areas with difficult topography and harsh environments, the TLS approach is suitable for monitoring surface subsidence. Additionally, Ghabraie et al. [48] detailed the physical description of strata movement relevant to mining, utilizing optical transducers, 3D laser scanners, and digital image processing techniques. With a few novel optical and laser-based monitoring equipment and a range of data processing techniques, they provided the physical modeling of subsidence caused by mining. In another study, In order to forecast the horizontal displacement and subsidence of the Gubei Coal Mine in Huainan, China, TLS was used as the data-collecting technology [49]. The research results show that the mining subsidence monitoring strategy outlined in this work can obtain surface deformation in a sizable mining-impacted area based on a limited area of observation.

3.3. Monitoring displacement in mining areas via UAV technology

3.3.1. UAV technology in monitoring deformation in mining areas

UAVs have shown great promise in monitoring land surface displacements, especially those resulting from subsurface mining [50]. In a case study published in 2020, Pawel et al. demonstrated how UAV photogrammetric data may be used to assess land surface deformation in Polish areas impacted by underground mining. In this study, in addition to relying on fragmented situational information, horizontal displacements are computed using tracking lines established in the field. The findings indicated that in optimal conditions, the XY coordinates and horizontal displacements may be accurately calculated to within 1.5–2 cm of ground sample distance (GSD), with a range of 2–3 cm GSD for heights and subsidence [51].

According to Yavuz [52], in order to ensure worker safety and sustain production, it is crucial to identify and monitor potential deformations in open-pit mines. Therefore, he developed a deformation map for a marble quarry located in Eliktekke village, Amasya province, Turkey. This map was created using orthophotos and DEMs from UAV flights that were done at specific intervals.

3.3.2. UAV technology in monitoring ground subsidence in mining areas

According to Suh & Choi [53], due to challenges with accessibility, human-based subsidence mapping and surveying techniques have mistakes, omissions, and missing data. Furthermore, it is extremely difficult for people to monitor and explore areas where mine subsidence occurs because of safety concerns. As a result, the significance of employing UAVs to easily collect data in inaccessible places is growing. This technique complements traditional surveying technology in areas of mining subsidence by enabling precise, timely, affordable, and safe surveying and mapping [54]. In this study, mining-related subsidence zones and tailings dams were monitored using UAV.

Identifying ground subsidence is carried out in all kinds of mines such as underground, open-pit, and closed mines. While Suh and Choi (2017) mapped the sinkhole subsidence caused by hazardous mining in a closed mine [53], Ge et al. [55] created a map of mine subsidence related to underground mining in Australia's New South Wales. In these mines, they employed a UAV to map the underground mine subsidence, assess the safety of high wall slopes, and estimate the stockpile's volume. Findings show that images captured by UAVs and processed using digital surface models (DSM) are much more realistic and faster than other methods. This technology was also used in the study by Ignjatović Stupar et al. [56], where UAV photogrammetry technology was employed to compute the short-term mining subsidence parameters at the Wangjiata coal mine located in Inner Mongolia, China, as well as to identify the surface dynamic subsidence basin created by underground coal mining. In another study, Dawei et al. [57] confirmed that a UAV technique can quickly get the surface dynamic subsidence basin of coal mining areas with reliable mining subsidence variables. With this approach, mining subsidence characteristics might be predicted with more precision and a greater amount of collected data. In a similar manner, Pal et al. [58] calculated the surface subsidence using cloud-to-cloud analysis. In order to assess the degree of subsidence and identify areas of dirt dumping or sinking holes, a UAV-based 3D point cloud comparison was also carried out. The collected results showed that the suggested approach offers a foundation for additional study on surface sinking above underground excavations in which excavation is simulated by terrain reclamation.

3.3.3. UAV technology in monitoring of landslides in mining areas

In order to record landslides and inaccessible regions of the Nástup Tušimice mine in the North Bohemian Brown Coal Basin, Vrublová et al. [59] used UAV technology. Aerial photos obtained automatically with a UAV were used to construct an orthophoto and a three-dimensional (3D) model of the landslide zones. As a result, an appropriate measurement technique for operational targeting of landslides and hard-to-reach areas of the mining sites can be discovered.

3.4. Monitoring displacement in mining areas via remote sensing technology

3.4.1. Remote sensing technology in monitoring deformation in mining areas

According to Kumar et al. [60], in and around mining sites, surface deformation is a frequent occurrence. A space-based SAR approach is a promising tool for monitoring land deformation. To stop additional harm to the mine's surrounding developed regions, as well as other susceptible structures and landforms, land displacement must be monitored. Thus, to find surface deformation in and near the Jharia coalfield, they use time series interferometric SAR data. Besides, the benefits and characteristics of satellite radar interferometry over alternative geodetic surveying methods are discussed in the study [61]. They believed that in order to comply with the current gauging standards, it is relevant to integrate satellite radar interferometry in the undermined land deformation monitoring, especially during mine closure. According to Tamrat & Hussien [62], synthetic aperture radar interferometry, or InSAR, is a technology that was created in the 1960s and has the ability to provide continuous, high-resolution, all-weather space coverage. Thus, it may fulfill the needs of slope monitoring, compensate for the absence of discrete points in traditional ground measurement, and offer subsidence areas for space surface deformation information for a brief period. In the study Hu et al. [63], LT-1 InSAR interferometry is used in Datong, China, to monitor surface deformation dynamics in the mining displacement region. Using LT-1 and Sentinel-1 data, displacement and velocity fields were produced, and subsidence bowls were extracted from the DInSAR output. The results show that displacement values have been trending upward and that the areas of the subsidence bowls have been expanding over time. Also, using Sentinel-1 images, Yu Bing et al. [64] monitored the displacement in the Buertai coal mine in China. The study concluded that mining activities have a close relationship with the influencing range of the deformations and the variation in the deformation amplitude of the time series in various years. Similarly, Li et al. [65] employed Sentinel-1A images and the Small Baseline technology to collect the surface deformation information in the Huangling Mining area. The findings revealed that underground coal mining is the primary source of subsidence in this region.

Besides, Hu et al. [66] used China's ZY-3 satellite stereo data to suggest a method of extracting surface deformation by merging multi-temporal digital surface models (DSMs) with image homonymous characteristics in the Fushun coalfield of China. The findings show that by integrating image features with DSMs produced from ZY-3 satellite stereo imaging, more quantitative features and specific surface deformation may be extracted in mining sites. Also related to using In-SAR technology, Long et al. [67] proposes a unique approach that combines ensemble learning with Multi-Temporal InSAR data to forecast surface deformation in mining areas. This study presents a new and effective framework for surface deformation prediction in mining regions, highlighting the use and promise of ensemble learning and MT-InSAR technology for this kind of surface deformation prediction. Additionally, in order to solve the challenge of precisely tracking complete deformation fields over mining areas using Synthetic Aperture Radar (SAR), Wang et al. [68] suggested a method for obtaining complete deformation fields by fusing deformation data from sub-band InSAR, Differential Interferometric SAR (D-InSAR), and offset-tracking using the probability integral model. In the same way, Zhang et al. [69] determined mining deformation across dense vegetation areas using multi-platform SAR photographs. Coherence maps have been employed to identify high-quality interferograms, and MSBAS-InSAR techniques are chosen to retrieve mining deformation. The derived findings showed that during the investigated period, mining operations generated significant ground displacement in the Fengfeng mining area. Moreover, large-scale deformation that takes place in mining sites is monitored using sub-band InSAR. Sub-band InSAR can lessen the number of interference fringes and the challenge of unwrapping; however, the concurrent introduction of significant noise reduces the precision of monitoring, and the probability integral method is more widely used in the prediction of mine subsidence [70]. In the study Chen et al. [71], the Yineng Coal Mine's surface deformation field was obtained by integrating distributed scatterer InSAR, the probability integral method model, and an arctangent time function. Using a remote sensing technique, the deformation reduction effect of backfill mining technology is examined for the first time, along with a detailed analysis of the geographical and temporal evolution characteristics of surface displacement. Additionally, integrating SBAS InSAR and Logistic Function can be used to improve the accuracy of monitoring mining surface deformation. Ultimately, the high-precision time series deformation findings in the mining area were finally adjusted and obtained [72].

3.4.2. Remote sensing technology in monitoring ground subsidence in mining areas

According to Zhang et al. [73], InSAR has emerged as a cost-efficient, precise, and successful method for surveying and tracking land displacement. Therefore, in their study, Sentinel-1 satellite photos with a 6 or 12-day revisiting time are utilized to lessen the impact of temporal decorrelation and enhance the capacity to detect a deformation gradient. The results showed that InSAR is a helpful tool for detecting land subsidence in mining regions and offers more information for environmental mine restoration. Similarly, in the study Zhang et al. [74], using 20 ascending Radarsat-2 photos, a modified time-series InSAR approach is used to obtain ground movement in Huainan over nearly two years. The detection of land subsidence in central coal mining districts suggests that underground mining is the primary source of the subsidence. Moreover, monitoring land subsidence in mining areas presents a chance to strike a balance between mine extraction, land resource preservation, and land reclamation. Therefore, Hu et al. [75] focused on a case study of the Yanzhou mining area (YZMA) and suggested a hybrid methodology that combines digital elevation model (DEM) difference analysis, relational model establishment, and multiscale edge detection to provide a new method for dynamic monitoring of land subsidence. In the study of Li & Wu [76], remote sensing and image fusion were used to monitor subsidence caused by mining. They employed TM30 and 10 m (SPOT) resolution photos of the Huainan mining region in their experiment. A good result is obtained when mining-induced subsidence is monitored using the fusion photographs.

Besides active mines, this technology is also applied to monitor subsidence in abandoned mines. Long-term subsidence over abandoned coal mines can have a negative influence on more modern surface developments, whether they be residential or commercial. The assessment of subsidence risk can be improved by using remote sensing, particularly lineament analysis of pictures and images, which can provide details about less visible geologic structures (such as faults and fractures) that affect subsidence.

3.4.3. Remote sensing technology in monitoring landslides in mining areas

In order to lower the danger of disaster in landslide-prone locations, mine landslide susceptibility evaluation is essential. In other words, early warning systems and dynamic monitoring are essential for controlling and reducing this hazard. Liu et al. [77] identified the shortcomings of the conventional measuring techniques used for large-scale landslide monitoring and suggested a high-resolution remote image-based approach for widespread field monitoring of landslide displacement. Besides, the characteristics of landslides require an inverse analysis of slope tracking data in order to determine the origin, extent, and temporal evolution of the disasters as well as to further estimate the risks of future disasters. Thus, Liu et al. [78] used multisource remote sensing techniques to look into the Songmugou Landslide. The findings suggest that the evolutionary mechanism of landslides can be reliably predicted and backanalyzed using this approach. In the study of Tabish et al. [79], a novel system will be created for landslide remote monitoring, and 53 systems will be installed on the landslide body in the Luoshan mining region, which will make up the landslide remote tracking network. The findings indicate that the following benefits of this system include early warning for landslides, intelligent transmission across long distances, and real-time monitoring. According to Karagianni et al. [80], one of the most common large-scale disasters that can impact both urban and natural environments is a landslide, which frequently results in extensive property loss, huge destruction, or even fatalities on a global scale. In this study, data from the Sentinel-2 and Landsat 8 satellites, collected both before and after the incident, are being used to investigate a complicated series of landslides that happened in the Amynteon lignite mine in northwest Greece. In another research Jiao et al. [81], to locate landslides and examine the deformation evolution process of these landslides, multitemporal satellite pictures were utilized to derive deformation information from this location. The obtained results showed that in addition to aiding in the prevention of geological disasters, the identification and analysis of these landslide dangers and the disaster chain serve as a resource for the early detection and study of comparable disasters.

3.5. Monitoring displacement in mining areas via a hybrid method

3.5.1. Hybrid method in monitoring deformation in mining areas

GNSS technology can be used not only alone but also in combination with other methods, such as InSAR, to predict deformation caused by mining. In some studies, the interferometric synthetic aperture radar method is used to verify the results of monitoring ground motion phenomena generated by underground mining activities using GNSS data [82]. Similar to the above study, which also related to accuracy assessment, Du et al. [83] generated 3D ground surface deformation information by using the GNSS static observing network system in the mining area at the southwest foot of the mountain. The results showed that the displacements recorded by GNSS and the estimated value found by InSAR agree rather well. In addition to using inSAR to verify GNSS results, combining these two technologies in subsidence monitoring is also popular. Tondaś et al. [84] proposed an integration procedure to monitor deformation in the Upper Silesian coal mining region (southern Poland) that considers the advantages and disadvantages of GNSS and Differential Interferometry SAR (DInSAR) monitoring approaches. In addition, Li et al. [85] monitored and examined deformation in the Kunyang phosphate mine fusion using GPS and InSAR data. The results of this study offer a solid scientific basis for managing and preventing the risks associated with landslides, collapses, and other unknown geological hazards resulting from mining operations at this mine. Similarly, based on the combination of GNSS and InSAR observations, Zhou et al. [86] proposed an improved fusion technique for monitoring this 3D deformation in a mined-out region. The findings showed that this method can be applied to obtain three-dimensional displacement fields, which can then serve as a basis for secure mining operations in the area. Furthermore, Bo et al. [87] proposed the use of the GNSS approach interferometric reflectometry (GNSS-IR) to measure the ground surface deformation caused by underground coal mining. The results indicated that this integration might be viewed as a novel method that can continually and affordably detect surface movement.

In another study of Li et al. [88], an interferometric synthetic aperture radar time series analysis was used to monitor the deformation of Yang Juzhuang village, a residential region in the Huainan mining zone (China). Thirteen Sentinel-1A images were used to detect the vertical displacements. The obtained photos and the GPS measurement results are compared to confirm the method's validity and applicability.

3.5.2. Hybrid method in monitoring ground subsidence in mining areas

3.5.2.1. Combination of GNSS and InSAR. According to Ref. [89], it is expensive and time-consuming to use traditional subsidence monitoring methods, such as levels, total stations, and GPS, because they can only measure point-by-point. By utilizing multisource satellite SAR data over a mining location southwest of Sydney, Differential Interferometric Synthetic Aperture Radar (DINSAR) has been investigated as a complementary alternative to GPS and GIS. In study by Hu et al. [32], time-series DInSAR technology combined with several GNSS monitoring stations was used as a new technology to analyze the accurate and reliable surface motion law. The study's conclusions can provide a strong scientific basis for calculating mining subsidence, assessing the harm done to buildings or other structures, investigating land damage, and assisting with environmental management programs. Besides, The piecewise linear mapping between D-InSAR data and GNSS data can be found using the weighted total least-squares method to assess subsidence in mining in a complete manner [90]. Particularly in areas with notable gradient subsidence, this mapping can be utilized to enhance the results of traditional D-InSAR monitoring.

3.5.2.2. Combination of GNSS and UAV. Nowadays, better technologies to monitor mine subsidence are also being researched in order to save costs and enhance security. Combining GNSS and UAV technology is believed to be an effective means to rapidly collect vast volumes of data. Therefore, Wang et al. [91] used this suggested method in a study to identify mine subsidence. The findings show that this integration is suitable for detecting mine subsidence.

GNSS real-time kinematic and total station tachymetry were used in the study of Stupar et al. [56] to confirm the accuracy of the UAV-based subsidence determination at the Velenje coal mine. The presented approach helps provide the groundwork for future research on surface subsidence on underground excavations with the use of simulations implemented by mine reclamation as excavation moves forward.

3.5.2.3. Combination of GNSS and TLS. Furthermore, to monitor some surface mine activities, TLS can be integrated with GSNN technology. This technique combined the benefits of TLS and GSNN. To monitor mining subsidence, Zhou et al. [92] created a ground surface digital elevation model of the mining area using a combination of GPS and TLS monitoring technology. Because TLS has access to subsidence basin data in the mining area, it can provide additional benefits and make up for the "point"-shaped observational deficiencies of GPS.

On the other hand, laser scanning topographic monitoring helps detect and avoid problems that could harm the environment and people in areas where mines have ceased. Terrestrial laser scanning was done on the corresponding surface of the Victoria mine, Slănic Prahova salt deposit, Prahova County, using a network facilitated by GNSS technology. The results demonstrate that the use of laser scanning reduces implementation time for measurements, facilitating precise target interpretation [93].

3.5.2.4. Combination of UAV and TLS. Using UAV and LiDAR data, Jóśków et al. [94] assessed the vertical changes of the mining regions. TLS data was used to compare the accuracy of the approaches. Compared to UAS LiDAR sensors, UAS photogrammetry allows for the acquisition of less noise data and more accurate terrain subsidence assessment results. The experiments demonstrated that UAV photogrammetry can detect medium-scale deformations, but the analysis should be done in non-vegetated areas and outside the growing season to ensure optimal data quality.

Horizontal displacements often do not exceed a few decimeters in size, but they should nevertheless be observed to evaluate and reduce any potential negative effects. In order to do this, Puniach et al. [95] automated the process of identifying the vector field of horizontal displacements caused by underground mining in order to do this, using UAV-based ultra-high-resolution orthomosaics. The accuracy was evaluated both against independently determined displacements using terrestrial laser scanning and against manual displacements based on ortho mosaics produced by UAVs. The obtained results showed that the precision is influenced by both the resolution of the analyzed images and the accuracy of the georeferencing measurements.

3.5.2.5. Combination InSAR and UAV. The use of unmanned operations to monitor mining-induced land subsidence is increasing. Zhu et al. [96] performed a thorough comparison investigation of the accuracy of recorded ground deformation offered by UAV, Small Baseline Subset (SBAS), and Differential InSAR at the Banji Coal Mine. The integration of the above technologies has taken advantage of their strengths, thereby allowing the achievement of visual, comprehensive, and highly accurate monitoring of subsidence basins in mining areas.

4. Results and discussion

The literature shows that geospatial technology, including GNSS, UAV, TLS, and remote sensing (RS), has been applied to monitor displacement caused by mining. Furthermore, the fusion method of the above technologies is also used to promote their advantages and limit their disadvantages. Deformation, subsidence, and landslides in all types of mines, such as underground mines, open-pit mines, and closed mines, can all be determined using the above technologies. The number of studies applying this technology to identify displacement in mining areas is presented in Figure 2. According to the scientific publications mentioned above, the remote sensing method, in particular InSAR, is the technique most frequently utilized to determine displacements brought on by induced mining. The methods used after RM are hybrid and GSNN because of their high accuracy and many advantages. The use of UAVs and TLS to determine mining-induced displacement has been less studied than the above methods.

The restriction of InSAR is the adverse effect of the atmosphere on observations because of its heterogeneity. But among the techniques for sensing surface displacements, InSAR is superior because of its numerous benefits. It first makes it possible to investigate historical occurrences, which is crucial, particularly in monitoring displacement with

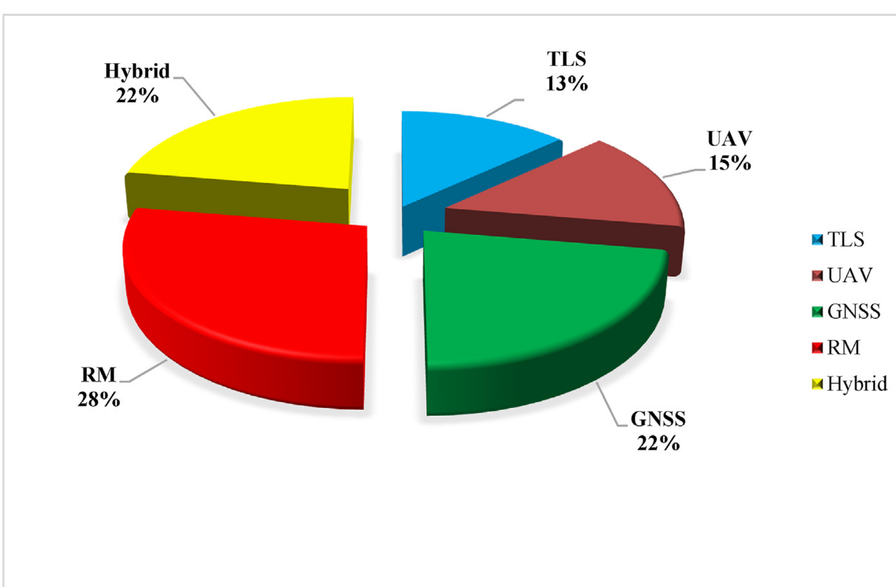

Fig. 2. The number of studies applying geospatial technology to identify displacement caused by mining.

measurement accuracy comparable to GNSS measures. In addition, direct field measurements or monetary outlays are not necessary with InSAR. Satellite imagery is readily available and can cover large areas and difficult-to-reach locations. Additionally, the determination of the spatiotemporal development of surface displacement over an extended period (many months or years) is made possible by the use of time series, such as the small baseline subset approach [97]. This benefit is quite significant for the process of figuring out subsidence and deformation. Besides, rapid measurements for large areas and locations that are inaccessible to people are the distinguishing characteristics of aerial photogrammetry and LIDAR data. LIDAR observations and aerial photogrammetry are often performed upon request and related to the creation of an orthophoto map or DTM.

UAV technology, compared to other monitoring techniques, can collect data quickly, have a short revisit duration, and operate simply. UAV technology might solve the low-resolution of satellite photos as well as eliminate the time-consuming groundwork of total stations, GPS, etc., and might provide a 3D visualization impact of the study region. Besides, UAVs with several sensor types could gather data from multiple sources for ongoing surveillance, and when the UAV flew at low altitudes, it could quickly capture photos at the centimeter scale [98]. UAVs are, nevertheless, also susceptible to a number of internal and external factors, such as weather, GPS signal strength, and maintenance issues. UAVs may be harmed by bad weather, which could prevent them from completing their missions and potentially cause flight delays [16]. The most difficult use case for remote sensing unmanned aerial vehicles (UAVs) is underground mining, which demands a different navigation and communication architecture than UAVs used for surface mining applications [99].

Moreover, the GSNN method enables continuous measurement of station coordinates and high accuracy, while the measurements can be conducted in a variety of weather situations, day and night. This makes it possible to identify the displacements generated by induced mining. The literature revealed that the GNSS technology has the following benefits for tracking mining-induced displacement: high observing precision, a fast and flexible network structure, and broad use [35]. In addition, because RTK can quickly and accurately gather positioning data with millimeter-level accuracy, the experiment's findings suggest that it can be widely used in small-scale displacement monitoring [100]. Moreover, this system can give real-time 3-D displacements and continually collect data in all weather situations, including wind, rain, and haze. Thus, GNSS is suitable for studying landslides. The PPP-GNSS method is useful for tracking landslides that fluctuate slowly and happen almost instantly; although it can provide absolute coordinates directly without the use of a reference station, its accuracy can only be reached at the centimeter level after tens of minutes [24]. Even though it can achieve great accuracy when used in conjunction with conventional measuring techniques, GNSS-RTK is not very dependable and is susceptible to weak satellite signals [98].

Another low-cost method that is highly accurate is TLS technology. This method offers objective, more accurate, more precise data regarding discontinuity orientations. Mine surfaces can be thoroughly surveyed thanks to laser scanning technology. Additionally, it is simple to acquire the characteristics of the discontinuities that are situated in unreachable regions. TLS is one of the most precise remote sensing techniques for obtaining spatial data with a measurement accuracy of a few millimeters or centimeters [41]. The use of TLS technology in monitoring displacement in mining regions brings many benefits related to accuracy, speed, environmental resilience, and large scale. The primary benefits of this method are time savings, increased point density, and improved accuracy in comparison with GNSS and traditional approaches. Additionally, one of the important benefits of this technology is that TLS operates without contact, which removes the possibility of damage or interference that conventional measurement techniques could cause. Although this method has a high measurement precision, it also has the drawbacks of being labor-intensive and time-consuming [41].

5. Conclusion

The present study reviewed recent publications related to the use of geospatial technology in displacement determination. The findings indicated that multiple geospatial technologies, including GNSS, UAV, TLS, and remote sensing, can be utilized to monitor deformation, subsidence, and landslide processes in mining areas. The results of the review of studies related to the above applications have also pointed out the positive and negative aspects and scope of use of the applied methodologies. Moreover, the combination of the above technologies is also encouraged in displacement monitoring because it takes advantage of their benefits and overcomes their drawbacks. As a result of the analysis, it was shown that the integration of

GNSS and InSAR methods is the predominant technology in displacement identification caused by mining. In addition, the method most commonly used to identify displacements caused by induced mining is InSAR. The study's results can be used as a reference when choosing a method to monitor deformation, susidence, and landslide in the mining area.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

None.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgements

Thanks to reviewers and editorial comments for their invaluable comments, which helped us to improve the manuscript's quality.

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