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Review paper

# MONITORING TECHNIQUES FOR SUBSIDENCE INDUCED BY MINING OPERATIONS: A REVIEW

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**Abstract**

*Mining-induced ground deformation, particularly subsidence, poses a major challenge to the safety, efficiency, and environmental sustainability of underground mining operations. This paper presents a comprehensive review of modern monitoring techniques used to detect and analyze rock mass movements and surface deformations. The review highlights that no single method is universally sufficient; however, the combined application of multiple techniques significantly improves the reliability and accuracy of subsidence detection. Effective monitoring is crucial for early risk identification, informed decision-making, and ensuring the long-term stability of mining environments.*

***Keywords**: monitoring, subsidence, mine safety*

## 1. INTRODUCTION

Underground mining activities often cause complex geomechanical changes in the surrounding rock mass, with ground subsidence being one of the most critical consequences. This gradual or sudden downward movement of the surface, driven by stress redistribution and underground void formation, poses serious risks to infrastructure, safety, and the environment.

As global demand for mineral resources increases, mining operations are expanding in depth and scale, intensifying deformations in both underground and surface zones. Effective monitoring of subsidence has therefore become essential for mine planning, risk management, and environmental protection.

A variety of geodetic, geotechnical, and remote sensing techniques are now used to track ground movements in real time. These methods support early warning, validate numerical models, and inform operational decisions. Ultimately, subsidence monitoring plays a key role in ensuring safety, optimizing mining efficiency, and protecting both infrastructure and the environment.

## 2. EXPERIMENTAL

Monitoring ground subsidence during mining activities is a critical component of modern risk management and safety strategies in the mining industry. Various methods and types of instrumentation are employed based on proven technologies and best practices established across the sector. Given the dynamic nature of ground deformation, the selection and application of monitoring tools may evolve over time in response to changing conditions and new insights. The recommended measurement frequencies for different phases of mining are based on initial estimates of how subsidence is expected to develop. However, as data becomes available during operations, it is essential to adjust the monitoring frequency to accurately reflect actual subsidence behavior and ensure that the collected data represents the true ground conditions.

### 2.1.Interferometric synthetic aperture radar (InSAR)

InSAR (Interferometric Synthetic Aperture Radar) is a highly effective remote sensing technique for detecting and measuring ground subsidence caused by mining activities. This method involves analyzing multiple radar image pairs captured over time to generate interferograms, which depict phase differences between the images. Each pixel in the interferogram reflects the phase shift, and by comparing these shifts across different acquisition dates, ground displacement can be accurately calculated. The resulting deformation data is then overlaid on satellite imagery, allowing for precise identification of movement patterns and affected areas. InSAR is particularly valuable for continuous, large-scale monitoring of surface deformation, providing critical information for risk assessment and decision-making in active mining regions [1].

### 2.2.3D Laser scaning

3D laser scanning technology offers a fast and accurate method for monitoring ground deformation by capturing high-density, three-dimensional coordinate data of the terrain. Unlike traditional point-based measurements, this method collects comprehensive surface point cloud data, enabling detailed spatial deformation analysis without the need to place instruments in hazardous collapse areas. The system typically includes a laser scanner, power supply, PC, and tripod, and allows for high-speed data collection while minimizing equipment exposure to harsh field conditions. However, its effectiveness can be limited by terrain complexity and line-of-sight requirements, as accuracy decreases with distance and obstructions such as forests and buildings may hinder scanning in large or uneven mining areas [2].

### 2.3.Global positioning system (GPS)

The Global Positioning System (GPS) is a satellite-based technology that provides precise positioning, displacement, and timing data worldwide. Known for its high accuracy, reliability in all weather conditions, and global coverage, GPS is widely used in monitoring various geological hazards such as landslides, dam deformation, and ground fissures. In subsidence monitoring related to mining activities, GPS detects changes in the three-dimensional coordinates of surface points, including both vertical and horizontal displacements. However, GPS is limited to surface-level monitoring and cannot fully capture the spatial extent of subsidence. Additionally, the vertical accuracy and geodetic height obtained through GPS measurements may not always be directly applicable for detailed subsidence analysis [3].

### 2.4.Global navigation satellite system (GNSS)

The Global Navigation Satellite System (GNSS) encompasses all satellite navigation systems, including GPS (USA), GLONASS (Russia), Galileo (EU), BeiDou (China), and various augmentation systems like WAAS, EGNOS, and MSAS. GNSS-based deformation monitoring is an efficient and precise method for detecting ground or structural movement. High-precision GNSS positioning, through static or real-time kinematic (RTK) observations, enables the detection of displacement by comparing coordinates over time. The system calculates position using signal travel time from satellites, though atmospheric interference introduces pseudo-range errors. GNSS monitoring stations are composed of multi-frequency receivers, antennas, batteries, solar power modules, and communication units, offering flexible installation and real-time or periodic data acquisition. The technology is widely adopted due to its high accuracy, reliability, and ease of use in diverse monitoring applications [4].

### 2.5.Unmanned aerial vehicle (UAV)

Unmanned Aerial Vehicle (UAV) photogrammetry involves using aerial cameras mounted on drones to capture continuous images of a target area. These images are combined with ground control points to produce 3D models and topographic maps. The UAV system includes hardware (flight platform, sensors, monitoring and support systems) and software (flight planning and data processing tools). Predefined flight parameters ensure efficient aerial surveys, while post-processing software corrects image distortions and generates accurate geospatial data. UAV photogrammetry is widely used for fast and detailed terrain mapping [5].

### 2.6. Borehole camera monitoring

Borehole camera monitoring technology is used to detect and assess the condition of mined-out areas by drilling boreholes from the surface or underground. A camera probe is inserted into the borehole to capture real-time images of rock fractures, voids, and caving boundaries. The technology provides visual and quantitative data on rock mass stability, roof thickness, and the geometry of mined-out spaces. It allows for early detection of roof collapse and helps monitor the progression of caving over time [6].

### 2.7. Time domain reflectometry (TDR)

Time Domain Reflectometry (TDR) is an electronic measurement technology originally developed for military applications and later widely used in the electronic and communication industries. It works by transmitting a step voltage pulse along a coaxial cable and detecting the reflections caused by impedance changes, which indicate faults such as breaks or deformations in the cable. When the cable is embedded in a cement mortar body, sudden tension and breakage reflect the location and timing of roof collapse. Although minor deviations may exist between the cable break point and the actual collapse location, the scale of the monitored rock mass ensures that TDR remains an effective method for assessing overall roof stability [7].

### 2.8. Microseismic monitoring

Induced mining activities can impact rock mass stability. Certain areas of a mine may become hazardous due to the progression of excavations and headings. As stress is redistributed, the rock mass responds with movement, which generates acoustic P and S waves either due to blasting or natural adjustments. To ensure production safety, microseismic monitoring systems are used in active mining zones to detect and analyze these movements [8].

### 2.9. Acoustic emission (AE)

Acoustic emission (AE) monitoring is a technique used to assess the stability of rock masses by detecting high-frequency elastic waves generated during rock deformation and failure. Unlike microseismic monitoring, which targets larger-scale rock movements, AE focuses on detecting signals from micro-fractures such as crystal breakage and intergranular cracking. These signals are converted into voltage and analyzed to determine fracture location, time, and energy. AE monitoring is applied to assess ground pressure in horizontal roadways and ore tunnel entrances, providing early warning for ground instability [9].

### 2.10. Electromagnetic radiation (EMR)

Electromagnetic radiation (EMR) monitoring is a method developed from the observation that electromagnetic anomalies often precede earthquakes. During the rock fracture process, significant EMR is emitted. By applying damage mechanics, statistical analysis, fractal theory, and supported by numerical simulations, laboratory tests, and field monitoring, researchers have identified the characteristics and mechanisms of EMR during rock failure. This method is used to predict dynamic events like pressure bumping. EMR monitoring assesses the extent and rate of coal and rock damage by analyzing signal amplitude and pulse count. It offers non-contact, easy-to-use monitoring, but its limitations include a small detection range and susceptibility to environmental and operational interference, as well as limited ability to accurately locate ground pressure events [10].

## 3. RESULTS AND DISCUSSION

This study presents a comprehensive review of current monitoring methods used in mining to assess ground stability and deformation. Each of the reviewed monitoring methods presents specific advantages and limitations, depending on the monitoring objectives, environmental conditions, and required spatial or temporal resolution. Remote sensing techniques like InSAR and UAV photogrammetry are effective for large-scale surface deformation detection but are limited in subsurface monitoring. In contrast, contact-based methods such as TDR, microseismic, and acoustic emission provide detailed information on internal rock mass behavior but require sensor installation. Electromagnetic monitoring shows promise for early warning of rock failure but is highly sensitive to external noise and has a limited detection range. GNSS/GPS and 3D scanning offer high precision for localized surface movement but are less suitable for detecting underground changes.

## 4. CONCLUSION

This study reviewed a range of modern monitoring technologies applied in geotechnical and mining environments. The analysis demonstrates that while each method offers valuable insights into rock mass behavior and ground stability, none is universally applicable under all conditions. Each technique carries inherent strengths and limitations related to spatial coverage, sensitivity, resolution, cost, and susceptibility to external disturbances. Effective monitoring in complex subsurface environments often requires a multi-method approach, where complementary technologies are integrated to provide more comprehensive and reliable data. Future developments should focus on enhancing data interpretation algorithms, improving sensor durability, and enabling real-time decision-making to increase safety and efficiency in underground operations.

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## REFERENCES

[1] Y. Chen, G. Zhang, X. Ding, Z. Li., Journal of Geospatial Engineering, 2 (1) (2000) 3-21.
[2] L. Wang, Z. Shangjun, J. Chuang, L. Jingyua, J. Kegui, T. Chaoqun, W. Tao, G. Qing-biao, KSCE J. Civ. Eng., 25 (4) (2021) 1-14.
[3] L. Ge, C. Rizos, S. Han, H. Zebker. Proceedings of 10th FIG International Symposium on Deformation Measurements, 19–22 March 2001, Orange, California, USA.
[4] Y. Cai, Y. Jin, Z. Wang, T. Chen, Y. Wang, W. Kong, W. Xiao, X. Li, X. Lian, H. Hu., Int J. Coal. Sci. Technol., 10 (2023) 32.
[5] S. An, L. Yuan, Y. Xu, X. Wang, D. Zhou., Geomech. geophys. geo-energy geo-resour., 10 (2024) 57.
[6] M. Pak, R.P. Preston, C. Groccia, J. Taylor., Proceedings of Underground Mining Technology, 2017, Sudbury, Canada.
[7] K.M. O'Connor, E.W. Murphy., Int. J. Rock Mech. Min. Sci., 34 (3–4) (1997) 230.e1-230.e15.
[8] S. Prahastudhi, A. Muttaqi, E. Sitorus, E. Riyanto, J. Geosaintek, 4 (1) (2018) 23.
[9] M. Khoshouei, R. Bagherpour, MGPB., 2019, pp. 19-32.
[10] E. Wang, X. He, X. Liu, W. Xu, Saf. Sci., 50 (4) (2012) 885-893.