APPLICATIONS AND ADVANTAGES OF GEOPHYSICAL METHODS IN UNDERGROUND MINING

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ABSTRACT. Geophysical methods play a crucial role in underground mining operations by providing valuable information about the subsurface geology, structural features, and potential hazards. Geophysical methods can provide valuable information in areas where direct access is limited or impossible, such as beneath thick layers of overburden, or in areas with difficult topography. Geophysical techniques, such as Electrical Resistivity Tomography (ERT), are widely used to map geological structures like faults, fractures, and bedding planes. This information helps in understanding the rock mass characteristics and potential zones of instability. Geophysical data can be integrated with geological, geochemical, and geotechnical data to develop comprehensive models of the subsurface. This integrated approach enhances the understanding of geological structures, ore body geometry, and rock mass behaviour, facilitating more informed decision-making in mine planning and development. Overall, the capabilities of geophysical methods in an underground mine encompass a wide range of applications, from geological mapping and resource exploration to hazard detection and ground stability monitoring, ultimately contributing to safer and more efficient mining operations.

Key words: electrical resistivity tomography, underground mine, geophysics.

ПРИЛОЖЕНИЯ И ПРЕДИМСТВА НА ГЕОФИЗИЧНИТЕ МЕТОДИ В ПОДЗЕМНИ МИННИ ДЕЙНОСТИ

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РЕЗЮМЕ. Геофизичните методи имат важна роля в подземните минни операции, като предоставят ценна информация за подземните геоложки условия, структурните характеристики на терена и потенциалните рискове. Геофизичните методи могат да осигурят ценна информация в райони, където директният достъп е затруднен или невъзможен, като например под дебели слоеве откривка или в райони със затруднен достъп. Геофизични методи като електротомографията широко се прилагат за картографиране на геоложки структури като разломи, фрактури и фундамента. Тази информация подпомага разбирането за характеристиките на скалите и потенциалните зони на нестабилност в рудниците. Геофизичните данни могат да бъдат интегрирани с геоложки, геохимични и геотехнически данни, така че да бъде създаден достоверен модел на подповърхностното пространство. По такъв начин се подобрява разбирането за геоложките структури, геометрията на рудното тяло и поведението на скалната маса, което от своя страна води до по-информирано вземане на решения при планирането и развитието на мините. Като цяло, възможностите на геофизичните методи в подземните рудници обхващат широк спектър от приложения, от геоложко картографиране и проучване на ресурси до откриване на вероятни рискове и мониторинг на стабилността на земята, като в крайна сметка допринасят за по-безопасни и по-ефективни минни операции.

Ключови думи: електротомография, подземен рудник, геофизика.

Introduction

Geophysical methods are commonly used for rapid data acquisition, allowing for efficient coverage of extensive areas in a cost-effective manner and have demonstrated their capability in mining projects of various scales.

A lot of case studies worldwide demonstrate the efficacy of geophysical methods in detecting underground openings. The current research is focused on localising man-made voids and cavities in underground mining conditions (Aleksandrova, et al., 2019). As Orfanos mention, cavities, voids, abandoned mine workings, and any kind of underground opening can be hazardous in geotechnical and environmental applications (Orfanos and Apostolopoulos, 2012).

The collapse of material overlying abandoned underground mine voids can indeed be a significant issue, particularly when it is coupled with fluctuations in water levels within these voids.

According to several researchers, cavities created by underground coal mining can be partially or fully filled with air, water, or sediment (Rodríguez, 2019; Van Schoor, 2002; Zhou et al., 2002). In areas with a history of mining activities, abandoned mine workings or old mine shafts can pose risks to current mining operations. Electrical resistivity tomography (ERT) can assist in detecting these subsurface features by identifying anomalies in electrical resistivity that are associated with man-made voids or infrastructure. Recognising and mapping these features is crucial for ensuring the safety of underground mining operations and preventing accidents.

In all cases, these cavities can be identified by the contrast between their physical properties and the surrounding geological environment. Electrical resistivity is one of the primary physical properties that makes it possible to characterise these structures (Militzer et al., 1979; Putiska et al., 2012).

Mining operations in Bulgaria have been traditional since ancient times. At the modern stage, mining is a fast-growing industry with great added value. Its development is mostly due to the constant search and implementation of innovations and modern technologies both in production and in research activities, safety and care for the environment. These activities collectively aim to make mining operations more efficient, safer, and environmentally sustainable. Mining industry continues to evolve with the advent of new technologies since sustainability and responsible mining practices become increasingly important. As Bharti stated, the assessment of underground mine environment by geophysical survey is considered a challenging task (Bharti, et al., 2022). Considering this, the application of non-invasive survey techniques to collect additional information on mining conditions contributes both to increasing the degree of confidence in the available data and to enriching the knowledge of the terrain with specific information (Alexandrova, et al., 2019). One of the appropriate tools for this purpose is geophysical methods, and more specifically electrotomography. This method is widely used in the mining industry, proving its effectiveness in underground mining as well.

In the context of underground mining conditions, electrotomography can be used to:

- Map the structure of the rock and locate potential areas of cracking or faults.
- Optimise the planning of mining operations and extraction processes by effectively delineating the boundaries of the mineralised zone and waste.
- Provide information about subsurface conditions, including the presence of cracks, faults, and changes in rock types. This data can be useful for geotechnical evaluations supporting the design and stability analysis of underground structures.
- Monitor changes in subsurface conditions over time, such as water table fluctuations, movement of fluids (including mining-induced water), and changes in rock properties that may affect stability.

Electrical resistivity tomography can assist in optimising the layout of mining operations by delineating mineralised zones, waste zones, and providing information on the distribution of ore bodies.

It can also be useful in environmental monitoring purposes, such as assessing the impact of mining activities on groundwater quality and flow paths.

Description of the technology

Electrical resistivity tomography (ERT) is a valuable tool for detecting tunnels and underground openings, providing valuable information for engineering, construction, and geological investigations. Detecting cavities, tunnels or abandoned mine workings using resistivity tomography involves employing electrical resistivity imaging techniques to map subsurface structures based on variations in electrical conductivity. Resistivity tomography relies on the fact that different materials have different electrical resistivity values. According to Loke, electrical resistivity depends on geological material properties such as mineral composition, fluid content, porosity, salinity, temperature, and water saturation level (Loke 2004). By injecting electrical current into the ground through electrodes and measuring the resulting voltage, variations in resistivity can be detected, indicating the presence of subsurface features like tunnels or voids. When mining operations extract minerals from underground deposits, they create voids or empty spaces underground. If these voids are not properly backfilled or supported after mining operations cease, they can pose a risk of collapsing.

The material overlying these abandoned voids may become unstable over time due to factors, such as erosion, weathering, or changes in load distribution. This instability increases the likelihood of collapse.

Water infiltration into these abandoned voids can exacerbate the instability of the overlying material. Fluctuations in water levels, such as seasonal variations or changes in groundwater flow patterns, can exert pressure on the surrounding rock and soil, leading to erosion and weakening of support structures.

Within the mine workings themselves, fluctuations in water levels can also create instability. Water pressure can affect the integrity of support structures, such as pillars, beams, or walls, increasing the risk of collapse within the mine workings.

The geophysical survey is designed to meet some specific demands. To mitigate the risks associated with collapsed mine voids, various measures can be employed, including Electrical Resistivity Tomography (ERT) to identify voids, monitoring of water levels, stabilisation techniques like grouting or backfilling.

For the detection of subsurface voids, the electrical direct current methods have proved to be useful from a theoretical perspective (Spiegel et al., 1980; Sheets and Munk, 1997).

As Erkan stated, in the electrical direct current methods, the current electrodes (A and B) and voltage electrodes (M and N) can be arranged in several different geometries. For different array geometries, the geometric factor (k) changes according to the type of array. These variations offer many different practical applications of the electrical direct current methods depending on the type of target being investigated (Erkan, 2008).

The reliability of the geophysical images greatly depends on the correct and optimised application of measurements. The process of data recording is described by Sheets (2002). Data were gathered using automated resistivity measurements, enabling the placement of multiple electrodes at equal intervals along a survey line. Each electrode is linked to a computer-controlled device that sequences electrical pulses through various combinations of electrode configurations. The software records the applied current, resulting voltage potentials, and electrode geometry. Typically, the farther apart the electrodes are, the deeper the current penetrates (Sheets, 2002).

This geophysical technique is highly sensitive to various factors, and their consideration is crucial for its successful application. Electrical interference from nearby power lines, electromagnetic noise, and cultural noise (e.g., nearby machinery) can affect the quality of resistivity data, as well as correct application of the measurements.

Field measurements and results

The measurements are performed in underground mining conditions. Field measurements are shown in Figure 1. As mentioned by Azadi, in electrical resistivity imaging, according to the purpose and location of data collection, the electrodes are placed in specific arrays, and data collection is performed. The collected data (potential distribution or apparent resistivity) is then transformed into a distribution of actual electrical resistivity values using inverse modelling methods (Azadi & Ghanati, 2022).

Field measurements are performed with the Australian *ZZ Universal 96 Resistivity/IP Meter* (Figure 2).

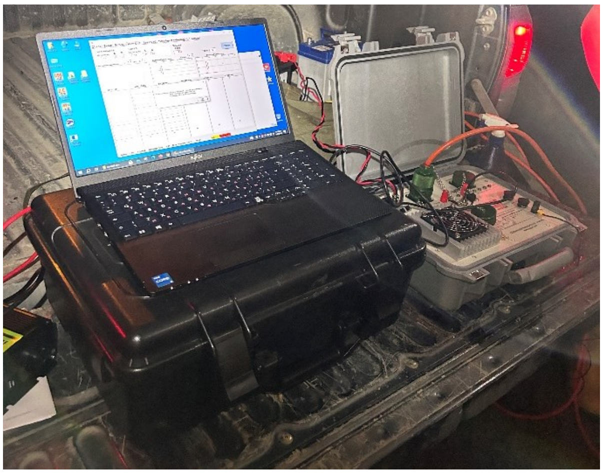

Fig. 2. ZZ Universal 96 Resistivity/IP Meter on the field

It is a leading geophysical instrument that provides accurate and reliable data on the electrical resistivity and induced polarisation (IP) of underground strata and objects. This innovative tool is designed to meet the increasing demands for accuracy and precision in mining, hydrogeology, construction, infrastructure sites, etc.

One of the most important steps in the survey is to ensure that the electrodes have good contact with the ground to ensure accurate measurements. Otherwise, the results can be affected by poor contacts between the media and the electrodes, leading to misleading data. In the specific underground conditions, the appropriate choice of electrodes are non-polarisable electrodes. They are specialised electrodes designed to minimise polarisation effects during electrical measurements.

Polarization occurs when there is a build-up of charge at the interface between the electrode and the electrolyte (soil, water, etc.), which can distort the measurements. Non-polarisable electrodes are engineered to reduce or eliminate this effect, providing more accurate and stable readings.

On the field, data were collected using automated resistivity measurements, allowing multiple electrodes to be placed at equal intervals along a survey line (Figure 3). Each electrode is connected to a computer-controlled device that sequences electrical pulses through different combinations of electrode configurations.

Fig. 3. Field measurements

A huge advantage of the instrument is the ability to display data quality immediately after the data collection is finished (Figure 4).

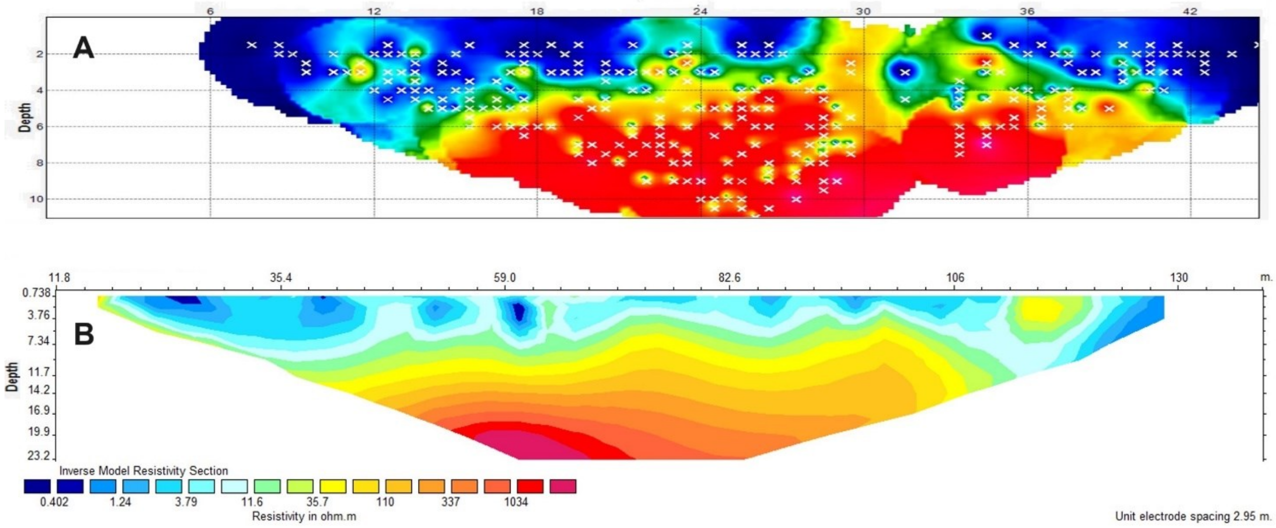

Fig. 4. Raw field data (A) and Pseudo-section representing the apparent resistivities of the subsurface (B)

The quality control on site enables the operator to review data directly in the field and respond promptly to eliminate any distortions, if possible.

The software records the applied current, resulting voltage potentials, and electrode geometry. Generally, the greater the distance between the electrodes, the deeper the current penetrates. One of the biggest disadvantages of the technology in underground conditions is that the space is limited and can not provide enough space between the electrodes. A very important step in field measurements is the choice of electrode configuration. The most used configurations are the Wenner array, Schlumberger, Dipole-Dipole, etc. The various options depend on the desired depth of investigation and the expected subsurface conditions.

In this case study, the Wenner array configuration was chosen to perform the survey. It consists of four equally spaced electrodes that are placed in a straight line. It is a symmetric array, meaning that the distance between adjacent electrodes is the same. The electrical device includes 96 electrodes, spaced 3 meters apart. The collected data are then processed and inverted using the *RES2DINV* computer program (Loke, 2001). This computer program automatically determines the 2D resistivity model for the observed data (Griffiths, 1993). The results of the electrical method are presented as a pseudo-section, representing the apparent resistivities of the subsurface as a function of depth in a vertical plane.

Data processing is a comprehensive and time-consuming process. It starts with detailed quality control including a review of the collected data for any anomalies or errors. The next step is inversion modelling, using the *RES2DINV* specialised software to process the resistivity data and create a resistivity model of the subsurface.

The interpretation process examines the resistivity profiles to identify anomalies and significant contrasts that may indicate voids, cavities, or other subsurface features.

Figure 5 shows a geoelectrical line located in an old mine shaft. The purpose of this measurement is to detect the presence of cavities behind the walls of the mine gallery. As seen in the interpreted section, electrotomography successfully detects the contrast boundary between the mine gallery, where the electrodes were placed, and the weak zone (Figure 5).

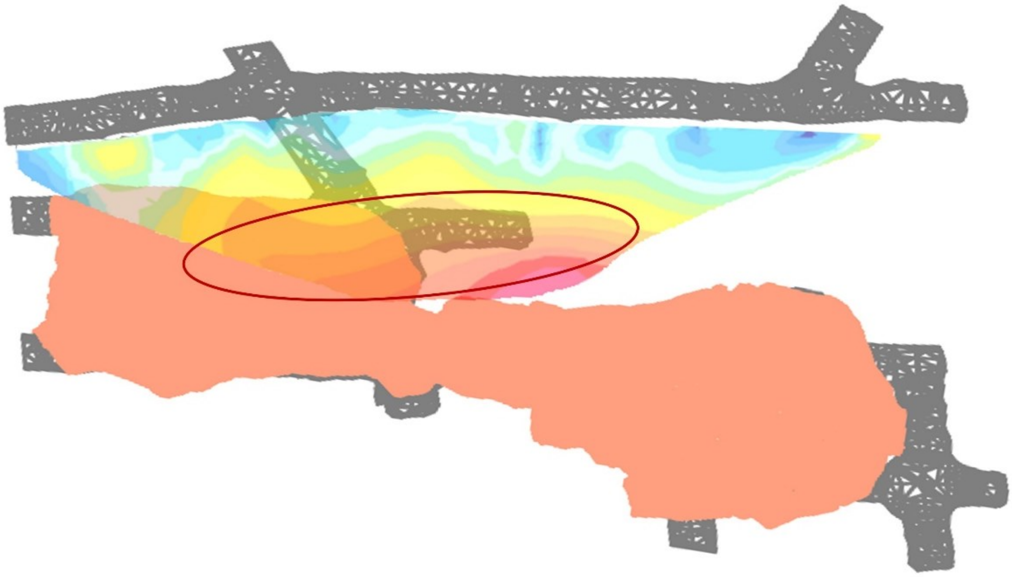

Figure 5. Geoelectrical line along the mine gallery

By analysing the resistivity data, anomalies that indicate the presence of cavities can be identified. High resistivity anomalies may indicate air-filled cavities, while low resistivity anomalies may indicate water-filled or sediment-filled cavities. Sediment-filled cavities may have resistivities that vary depending on the composition and saturation. In this case, the high resistivity response is considered as rock backfill and air.

Conclusion

Water levels in abandoned underground mine voids can create instability not only in the support structures within the mine workings but also in the material overlying these voids, posing significant hazards to both underground and surface environments. It underscores the importance of proactive monitoring, maintenance, and risk mitigation strategies in managing the legacy of abandoned mines.

Based on the conducted research, the following more important conclusions can be drawn:

- Geophysical methods can be used to detect the location of possible cavities or disturbances in geological strata, through measurements carried out underground.
- The application of geophysical methods during the various stages of design, construction, and monitoring improves the overall understanding of the spatial structure and the stability of the tunnels, allowing informed and timely actions to be taken if necessary.

Electrical tomography is a versatile and valuable tool in underground mining operations, providing critical information for geological, geotechnical, and safety assessments. It aids in optimising mining processes, improving safety, and ensuring environmental responsibility.

Geophysical methods prove a valuable tool for detecting cavities created by underground coal mining, especially when these cavities are filled with air, water, or sediment. It provides crucial information for geotechnical evaluations and ensures the safety and stability of mining operations.

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