Method of Predicting Surface Subsidence Caused by Underground Mining: A Review

Huy Dinh NGUYEN[1)], Trong Dinh TRAN[3)], Canh Van LE[2)]*

[1)] Faculty of Bridges and Roads, 55 Giai Phong Street, Hanoi University of Civil Engineering, Hanoi, Vietnam; ORCID https://orcid.org/0000-0002-2049-3338
[2)] Faculty of Geomatics and Land Administration, 18 Vien street, Hanoi University of Mining and Geology, Hanoi, Vietnam; ORCID https://orcid.org/0000-0002-3838-9950
[3)] Faculty of Bridges and Roads, 55 Giai Phong Street, Hanoi University of Civil Engineering, Hanoi, Vietnam; ORCID https://orcid.org/0000-0002-8113-9949
* Corresponding author: huynd@huce.edu.vn

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Abstract

In recent years, there has been a global increase in energy demand, with the extraction of underground mineral energy sources such as coal playing a significant role in the energy supply. However, the extraction of these natural resources always faces many challenges and risks. This process has created large voids, causing an imbalance in the original stress state within the earth and resulting in surface terrain deformations. Therefore, ensuring efficient extraction must be accompanied by safety measures. Among these, predicting surface subsidence due to underground mining is a crucial task. This paper presents an overview of the current method of predicting mining subsidence and their application scope. The result synthesizes various methodologies applied to different regions worldwide. Finally, the findings of this research can provide guidelines for establishing essential requirements for the application of surface displacement forecasting technologies due to underground mining.

Keywords: *subsidence prediction, underground mining, artificial neural networks*

1. Introduction

Due to the increasing energy demand, open-pit mining is not only no longer sufficient to meet the needs, but also less effective, leading mining companies worldwide have been transitioning from open-pit mining to underground mining method. However, one of the main drawbacks of the underground mining method is that overlying rock mass tends to move down to regain its new equilibrium state of stress, leading to the upper surface of the ground subsiding correspondingly, forming hollows and trenches, open cracks in the earth, abrupt steps, and extensive subsidence troughs, creating dangers to underground engineering structures and natural and artificial structures on the ground surface. In actuality, underground mining has exerted many negative impacts on environment and structures underground as well as on the surface, causing serious human and wealth losses; therefore, the forecast of surface deformation is a concern for many countries, numerous scientific centers, and scientists worldwide, with particular focus on countries with developing mining industries such as Russia, Germany, China, Poland, the United States [1]. In addition, new theories along with modern technology are increasingly being applied to enhance the accuracy of forecasting.

Russian scientists have been at the forefront of researching surface subsidence forecasting in mining operations. Through years of observational data collected from coal mines within the Soviet territory, basic formulas for calculating and forecasting ground subsidence were developed [2]. The establishment of formulas and forecasting models based on field observations in various mining regions by the Mining Mechanics and Mine Surveying Institute (VNIMI) at Saint Petersburg Mining University was reported at the World Mining Science Conference in 2008 and is still being utilized in Russia and several other countries, including Vietnam [3]. Many Chinese scientists have focused on researching surface subsidence forecasting in mines. In 2000, in the Journal of Mining Mechanics, Cui X.M, Miao X.X., and Wang J.A. [4] proposed a method applying nonlinear geometric theory to improve the reliability of surface subsidence forecasting. In 2015, Lei Nie and colleagues published a new model applying inverse tangent functions to estimate mining-induced displacement and deformation [5]. Ki-Dong Kim and colleagues studied forecasting the degree of subsidence in Samcheok city due to the impact of coal mining [6]. In Poland, many research projects have laid the foundation and developed fundamental theories on displacement, mining deformation in general, and forecasting methods in particular. The most important and successful research is by Knothe Stanisław at the Academy of Mining and Metallurgy in Krakow. Knothe's method has paved the way for the development of many subsequent forecasting methods [7].

In recent years, alongside the continuous advancement of science and technology, many new theories and algorithms have been applied in mining subsidence forecasting. The support of algorithms and computer models has enabled overcoming the limitations of traditional methods. In 2003, Ambrozic T. and Turk G. [8] first published the results of applying artificial neural networks in forecasting subsidence due to coal mining at the Velenje mine, Slovenia, using a 2-layer feedforward neural network. In 2011, Kang Zhao and Si-ni Chen [9] announced the application of artificial neural networks in subsidence forecasting for metal mining in China.

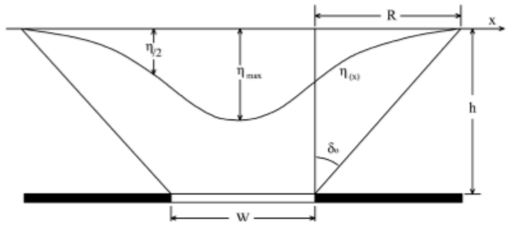

Fig. 1. Basic shifting cutting plane function [17]
Rys. 1. Podstawowa funkcja przesuwania płaszczyzny cięcia [17]

Hejmanowski and colleagues published a study applying artificial neural networks in forecasting surface mining displacement and deformation [10]. By 2017, author Kim Yangkyun and colleagues developed an artificial neural network (ANN) model to forecast subsidence in abandoned mines. The authors used survey results from 247 subsidence areas of 27 mines to validate the model [11]. To construct a map forecasting the impact of surface subsidence in the mine area, authors [12] utilized 7 input factors for ANN. In 2017, author [13] and colleagues used a feedforward neural network with a 9-7-6-1 structure to forecast the stability of transport and ventilation shafts of the Tabas mine, Iran. In Vietnam, Long and has applied the exponential function proposed by Knothe to forecast vertical displacement over time on the surfaces of Thong Nhat and Mông Dương mines [1], [14]. Research on forecasting vertical displacement of observation points on the surface over time was also addressed by author Khanh in a study applying the Kalman method in forecasting surface vertical displacement in mines [15]. Beside, Tam [16] and colleagues studied Prediction of underground mine's surface subsidence using a recursive multi-step forecasting model with an Artificial Neural Network shown that These results demonstrate that the proposed method and ANN model are suitable for the time-series monitoring data in mining areas.

2. Data and methodology

This study employed the systematic literature review approach to identify, evaluate, and interpret all pertinent research on the detection of surface displacements and deformations due to underground mining. The research on forecasting soil and rock displacement and surface deformation ultimately relies on data about geological characteristics, the physical properties of rock and soil layers, and mining technology. Researchers utilize suitable tools to estimate the values of displacement and deformation parameters as well as the displacement angles. Depending on the nature of the tool selection and problem-solving approach, forecasting methods can be categorized into different groups.

2.1. Group of methods based on empirical relationships

Common characteristics of this group of methods are based on empirical relationships determined based on actual measurement data in a specific area to predict surface deformations for that area. The more extensive and accurate the observational data, the higher the accuracy of the predictions. The broader the range of observational data, the more widely applicable the empirical relationship methods are for predicting surface deformations.

2.2. Group of cross-sectional function method

The group of methods involving the section function allows for the determination of vertical displacement at points on a cross-section perpendicular to the direction of the seam based on mathematical equations or descriptive tables of the displacement tank section. This research approach has been developed in many countries because it is relatively easy to use in forecasting and can be studied for application to new geological-mining conditions.

The coefficients in the equations or charts are determined experimentally from field survey data. The complexity of each method in the group depends on the number of factors considered in the geological-mining conditions, which are deemed important. The basic subsidence surface function has a form similar to equation (1) and has a shape as shown in Figure 1.

$$\eta = f(\eta, x, R) \tag{1}$$

This forecasting method can be subdivided into two groups: a group of formulas based on inflection points and a group of functions based on the center points of the mining area [17].

2.3. Group of Impact Function Methods

This method allows for the prediction of deformation at points on the ground surface. It is built on the theory that there is an influence zone surrounding the point to be predicted due to the extraction of an area within the sphere of influence affecting that point. A common assumption is that the influence zone has a circular shape. The hypotheses and scientific methods proposed by Keihorst have been applied and refined by later researchers, including Bals.

The advantage of the impact function method group is that it allows for the estimation of vertical displacement at any point on the ground surface within the influence zone of a mined area with an arbitrary shape. The application can be somewhat complex, and verifying accuracy is challenging. Moreover, drawing influence circles is only accurate in the case of flat-lying seam extraction, so this method is typically applied when extracting flat-lying and gently dipping seams.

2.4. Group of physical model methods

In many countries, small-scale material models representing different mining scenarios have been used for monitoring the vertical displacement process and have achieved varying degrees of success. By combining several materials such as sand, gelatin, a model of the mining panel similar to reality but on a smaller scale is built (Figure 2).

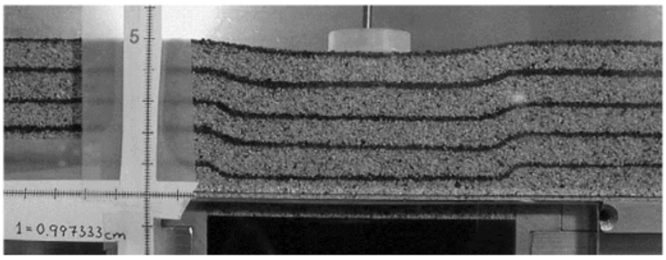

Fig. 2. Physical model made from dry sand [18]
Rys. 2. Model fizyczny wykonany z suchego piasku [18]

The advantage of this forecasting method is its ability to monitor the deformation and collapse mechanisms occurring in the rock and soil. It allows the observation of some characteristics that theoretical models may have difficulty representing. Importantly, this method can be applied to any geological and mining conditions, making it crucial for predicting the formation of displacement basins, especially suitable for studying new mining areas. It is also used as a supportive method alongside other approaches in forecasting surface displacement and deformation. The limitation of this group is the difficulty in constructing a model similar to the actual structure, so it mainly provides relatively qualitative results. Nowadays, thanks to the rapid development of information technology, this group of methods has been significantly improved, providing good efficiency and significantly increasing both qualitative and quantitative reliability.

2.5. Analytical Model Group

These models are based on examining ground displacement according to the laws of random environments, elastic environments, plastic environments, or viscoelastic environments, etc. Solutions from conventional models are typically sets of equations to predict vertical displacement, mainly in two-dimensional space. The finite element method and its variations are widely applied in modeling. Nonlinear analysis is also used to simulate the non-equilibrium state of soil and ground displacement.

A representative example of a random model is Litwiniszyn's research [18]. The author studied the movement of a random environment to explain the ground displacement process caused by mining. The results obtained are mathematical expressions recognized differently from expressions derived based on continuous environmental mechanics. It can be observed that because the random environment contains many factors with different degrees of freedom, solutions cannot be found in classical mechanics. Still, they can be found using other methods. Subsequent studies by the author using experimental models with dry sand confirmed that a random model can be used to study ground displacement processes.

2.6. Group of Impact Function Methods

Representative for the surface subsidence prediction method due to underground mining is the Knothe method, according to Knothe [7]. The relationship between the time parameter and the vertical displacement value can be described by a two-parameter exponential function. One parameter is influenced by geological and mining factors, obtained from observational data, while the other parameter represents the maximum vertical displacement. The formula proposed by Knothe allows predicting the quantity of vertical ground subsidence at a specific time.

However, subsequent studies have shown that the formula proposed by him does not fully describe the vertical displacement process due to mining activities, as the vertical displacement process of a point on the surface undergoes four stages, including the preparatory stage, the onset of displacement, the intense displacement stage, and the concluding stage. Therefore, an additional parameter is incorporated into Knothe's original formula to ensure that the graph accurately represents the entire vertical displacement process of the surface. Other methods have also been applied in forecasting surface deformation over time, such as the Kalman filtering method [15] and artificial neural networks [6], [11].

3. Application of artificial neural networks (ANN)

As mentioned above, forecasting surface displacements and deformations due to underground mining is a crucial task; therefor, new theories and algorithms are applied in forecasting mine displacement and deformation quantities, especially using artificial intelligence applications. Artificial Neural Networks are widely applied in various fields, including scientific forecasting. They have the ability to connect and integrate various parameters to identify and predict phenomena based on the cause-effect principle. Compared to forecasting methods based on formulas and coefficients determined from empirical data, the method of forecasting using artificial neural networks is considered a parameter-free approach and has the ability to forecast for areas with specific geological and topographical characteristics. This is a problem that needs to be addressed and applied in forecasting the displacement quantities due to the influence of mining processes. Forecasting the level of deformation due to mining using artificial neural networks is a modern approach. This method requires actual observational data from mining areas to train the network. However, this can be easily obtained and with much higher accuracy compared to collecting the necessary influencing factors as input for the aforementioned methods.

For many complex problems, to improve accuracy, the hidden layers should be increased, but this will complicate the network structure, increasing the time for training and adjusting the connection weights within the network [19]. According to Jeff Heaton [20], a neural network with two hidden layers can represent functions with any shape, so theoretically, there is no need to use networks with more than two hidden layers. Also, according to this author, problems requiring 2 hidden layers are rarely encountered, and in practice, there is no reason to use more than 1 hidden layer. More than one hid-

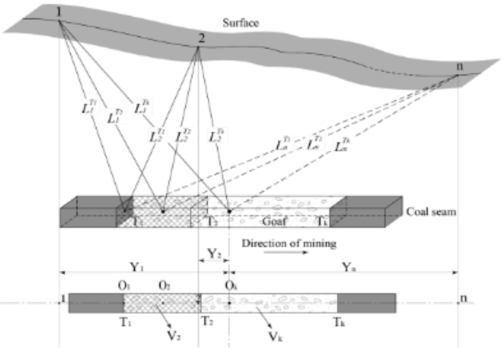

Fig. 3. Input factors of neural networks [1]
Rys. 3. Czynniki wejściowe sieci neuronowych [1]

den layer may be beneficial for some applications, but just one hidden layer is also sufficient [21]. Conversely, if there are too many neurons in the hidden layer, it can lead to issues such as "Overfitting" and long training times. Overfitting is when the output of the network is very accurate with the training set but performs poorly with new data (not in the training set). Recently, Nguyen Quoc Long [1] has researched and analyzed the factors influencing the deformation transfer process on the surface. We observe that the physical properties of soil and rocks will not change over time in the same exploitation area, so they are not chosen as input factors as shown in Figure 3.

4. Discussion

Base on a comprehensive review of the current methods for predicting mining subsidence and their application areas, the research findings can serve as a guide for setting up key requirements for the application of technologies to forecast surface displacement resulting from underground mining. Looking ahead, mineral extraction will continue to be a primary energy source, and forecasting subsurface displacement will remain a critical task in the geospatial industry. This review provides an overview of the current status of surface displacement forecasting, including current forecasting methods and their application scope. The findings reveal that the underground extraction process is highly complex, depending on numerous natural factors and mining technologies, leading to a variety of forecasting methods. Moreover, with the advent of new theories, algorithms, and artificial intelligence, surface displacement forecasting due to underground mining will become more accurate, ensuring safety in mining operations and reducing labor costs.

The discussion on the application of artificial neural networks (ANN) in forecasting surface displacements and deformations due to underground mining is particularly noteworthy. ANN, with its ability to connect and integrate various parameters to identify and predict phenomena based on the cause-effect principle, presents a promising approach to this complex problem. Unlike traditional forecasting methods that rely on formulas and coefficients determined from empirical data, ANN offers a parameter-free approach that can cater to areas with specific geological and topographical characteristics. However, the application of ANN in this context is not without its challenges. For instance, increasing the number of hidden layers to improve accuracy can complicate the network structure and increase the training time. Furthermore, having too many neurons in the hidden layer can lead to issues such as "Overfitting" and long training times. Overfitting is when the output of the network is very accurate with the training set but performs poorly with new data (not in the training set). Despite these challenges, the potential of ANN in forecasting surface displacement due to underground mining cannot be understated. With the continuous advancement of science and technology, it is expected that these challenges will be addressed, and the application of ANN in this field will become more widespread and effective. This will not only ensure safety in mining operations but also contribute to reducing labor costs, thereby making underground mining a more viable and sustainable solution to meet the escalating global energy demand.

The future of underground mining and the associated task of forecasting subsurface displacement looks promising, thanks to the advent of new theories, algorithms, and artificial intelligence. As the world continues to grapple with the escalating energy demand, these advancements will play a crucial role in ensuring the safety and efficiency of underground mining operations.

5. Conclusions

In the future, energy supply will still primarily rely on mineral extraction and forecasting subsurface displacement will remain a crucial task in the geospatial industry. This review provides an overview of the current status of surface displacement forecasting as well as current forecasting methods and their application scope. The obtained findings show that underground extraction process is highly complex, relying on numerous natural factors and mining technologies, leading to diversity in forecasting methods. Besides, with the new theories, algorithms and artificial intelligence, surface displacement forecasting due to underground mining will be more accurate, ensuring safety in mining operations and reducing labor costs.

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Conflicts of Interest

The authors declare no conflict of interest.

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Metoda przewidywania osiadań powierzchni spowodowanych eksploatacją podziemną: przegląd
W ostatnich latach nastąpił globalny wzrost zapotrzebowania na energię, a wydobycie podziemnych mineralnych źródeł energii, takich jak węgiel, odgrywa znaczącą rolę w zaopatrzeniu w energię. Jednak wydobycie tych zasobów naturalnych zawsze wiąże się z wieloma wyzwaniami i ryzykiem. W procesie tym powstały duże puste przestrzenie, powodując brak równowagi pierwotnego stanu naprężeń w ziemi i powodując deformacje terenu na powierzchni. Dlatego zapewnieniu skutecznej ekstrakcji muszą towarzyszyć środki bezpieczeństwa. Wśród nich kluczowym zadaniem jest przewidywanie osiadań powierzchni na skutek eksploatacji podziemnej. W artykule przedstawiono przegląd dotychczasowych metod prognozowania osiadań górniczych oraz zakres ich zastosowania. W rezultacie dokonano syntezy różnych metodologii stosowanych w różnych regionach świata. Wreszcie, wyniki tych badań mogą dostarczyć wskazówek do ustalenia zasadniczych wymagań dotyczących stosowania technologii prognozowania przemieszczeń powierzchni w wyniku górnictwa podziemnego.

Słowa kluczowe: *predykcja osiadań, górnictwo podziemne, sztuczne sieci neuronowe*