Innovative Approaches to Predicting Surface Subsidence in Inclined Seam Mining: A Comparative Study of Asadi, VNIMI, and KHCNM Functions

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Abstract

This study explores the accuracy and applicability of three advanced subsidence prediction methods—Asadi profile function, VNIMI subsidence function, and KHCNM subsidence function—under the challenging conditions of inclined seam mining at Mong Duong coal mine in Vietnam. By comparing predicted subsidence values with direct observation data, the research evaluates the precision of each method using statistical metrics such as actual deviation (Δ), root mean square error (RMSE), mean absolute error (MAE), and correlation coefficient (r). The findings reveal that both the Asadi and VNIMI functions demonstrate high accuracy, with RMSE values of 0.081 m and 0.080 m, and MAE values of 0.055 m and 0.059 m, respectively. The KHCNM function, while slightly less accurate, still provides valuable insights with RMSE and MAE values of 0.101 m and 0.076 m. The study underscores the importance of precise subsidence prediction in safeguarding surface structures and optimizing mining technology, recommending further research to integrate the strengths of Asadi and VNIMI functions for enhanced prediction across different sections of the subsidence basin. This comprehensive evaluation offers a promising pathway for improving subsidence prediction in inclined seam mining, contributing to safer and more efficient mining operations.

Keywords: *Profile function, inclined seam mining, Mong Duong coal mine*.

1. Introduction

The rules, intensity, and process of surface subsidence are influenced by topographical features, geological characteristics, stratigraphic properties, mining technology, and time [1]. The extent of influence of these factors is reflected through observation results. Therefore, observation results for each different mine or each area of a mine can be used as input to build prediction functions for specific cases. The predicted quantities will reflect the rules and properties of the surface deformation process and serve as a basis for selecting mining technology, construction methods, and maintenance of structures to prevent and mitigate negative impacts of mining activities, protecting surface structures.

Currently, there are many different methods to predict surface subsidence quantities due to underground mining, each method has its advantages, disadvantages, and suitable application conditions [2, 3]. According to the technical regulations for underground coal mining [4], most large coal seams in Quang Ninh basin, Vietnam are inclined seams. Moreover, most surface observation data is arranged in lines [5-9], so choosing profile function methods to predict surface subsidence under underground mining conditions in Quang Ninh is appropriate. Among these methods, popular ones in Vietnam include standard subsidence functions proposed by VNIMI [15], standard subsidence functions built from observation data in Quang Ninh [10], and Asadi profile function [11].

It is necessary to survey the accuracy of all three prediction functions under conditions at Mong Duong mine according to observation results to evaluate the applicability of each method under inclined seam conditions in Vietnam.

2. Characteristics of Coal Seams and Observation Data in Quang Ninh Basin

In Quang Ninh basin, large coal seams are mostly inclined or steeply inclined [4]. The rules and properties of surface deformation due to mining inclined seams have distinct characteristics compared to mining flat or gently sloping seams. Figure 1 shows the geological cross-section of some steeply inclined coal seams at Mong Duong mine [12].

Based on statistical data [13], there are 12 major underground coal mine projects managed by Vinacomin, which collectively hold total reserves of approximately 630 million tons. The distribution chart of these reserves, categorized by the thickness and dip angle of the coal seams, is illustrated in Figure 2. This chart provides a clear visual representation of how the reserves are spread across different seam thicknesses and angles. From this distribution chart, it becomes evident that the majority of coal seams with medium and large thicknesses, which possess significant industrial reserves, fall into the category of inclined and steeply inclined seams. These seams, referred to as inclined seams, are characterized by their substantial dip angles, making them distinct from flat or gently sloping seams. The prevalence of inclined seams in these projects highlights the importance of specialized mining techniques and subsidence prediction methods tailored to the unique challenges posed by such geological formations. Understanding the distribution and characteristics of these reserves is crucial for optimizing mining operations and ensuring the efficient extraction of coal resources.

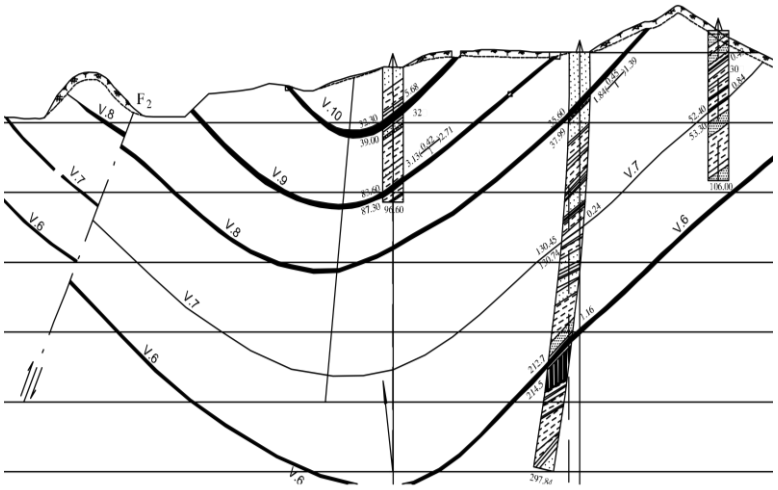

Fig. 1. Characteristics of the Inclined Coal Seams at Mong Duong Mine
Rys. 1. Charakterystyka nachylonych pokładów węgla w kopalni Mong Duong

Deformation observation systems in Vietnamese mines have been systematically arranged in lines, following both the strike direction and dip direction of the seams. This strategic arrangement ensures comprehensive monitoring of subsidence and deformation patterns. The length of these observation lines is meticulously planned based on the size of the mining face that is intended for extraction. Typically, the distance between individual markers along these lines ranges from 10 to 30 meters, allowing for detailed and precise measurements. Observation cycles are conducted at regular intervals, usually repeating every 2 to 3 months [9], to capture the ongoing changes and trends in subsidence. The number of observation cycles is carefully designed to meet specific research or operational purposes, often exceeding six cycles to ensure robust data collection. Given the characteristics of the existing line-type observation data, it becomes relatively straightforward to verify the accuracy of prediction results derived from profile prediction functions. This systematic approach to data collection and verification plays a crucial role in enhancing the reliability and effectiveness of subsidence prediction models, thereby contributing to safer and more efficient mining operations.

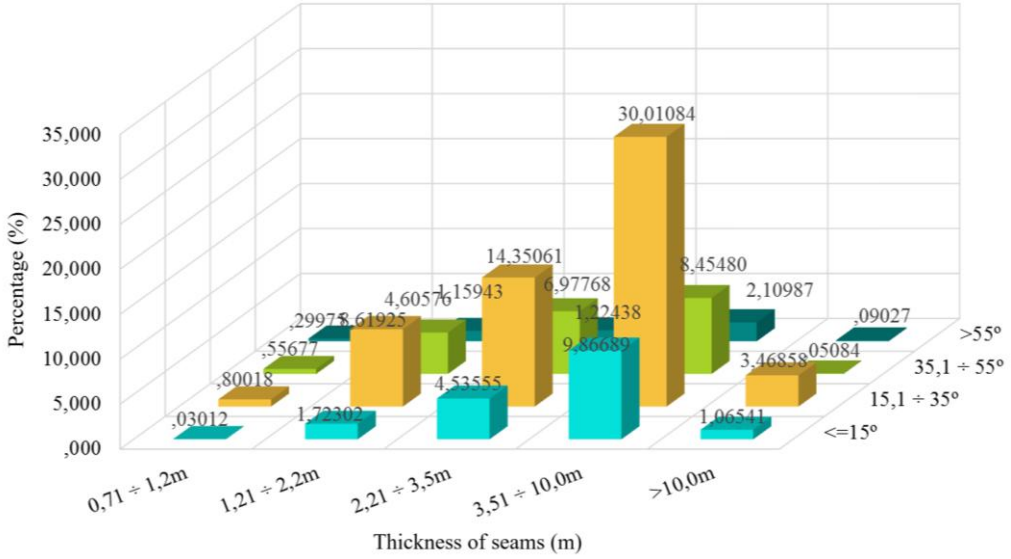

Fig. 2. Distribution Chart of Reserves for Underground Coal Mine Projects [13]
Rys. 2. Wykres rozkładu rezerw dla projektów podziemnych kopalń węgla [13]

3. Methodology

3.1 Standard Subsidence Function ($S_{(Z)}$)

Surface subsidence on basic cross-sections of displacement basins is determined according to the general formula:

$$\eta_X = \eta_{max}.S_{(Z)} \quad (1)$$

where:

- η_X is the subsidence of the point on the cross-section at a distance X from the center of the displacement basin;

- η_{max} is the maximum subsidence at the center of the trough; $S_{(Z)}$ is the subsidence curve function, determined from the lookup table.

- $Z = X/L_1$ hoặc $z = X/L_2$ corresponding to points on the basic cross-sections along the dip direction and strike direction of the coal seam (Figure 3).

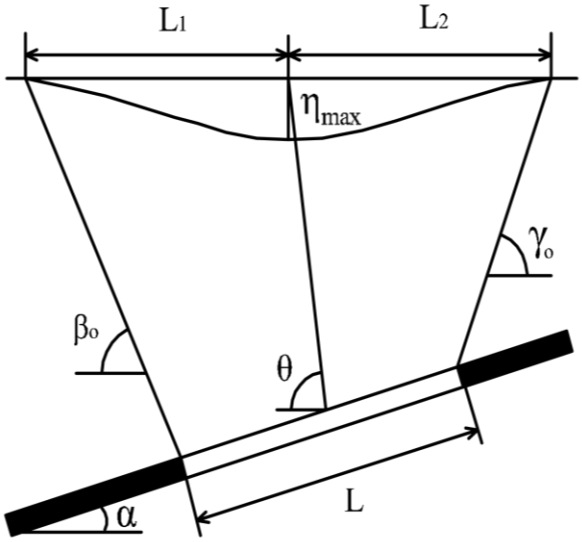

Fig.3. Subsidence Curve and Parameters of the subsidence trough

Rys. 3. Krzywa osiadania i parametry niecki osiadania

The Institute for Mining Surveying and Mining Geomechanics (VNIMI), part of Saint Petersburg Mining University, is a major scientific center specializing in research on displacement and deformation issues in mines. VNIMI's main direction is building formulas and experimental models based on field observation results from various mining regions. VNIMI's BTY deformation prediction function [14] has been built and published; it has been used in Russia and several countries worldwide, including Vietnam [15, 16].

The Institute for Mining Science and Technology (Vinacomin), based on observation results from many lines, synthesized and processed data; research results proposed standard subsidence functions for Quang Ninh [10]. Table 1 shows the lookup table for standard subsidence functions proposed by VNIMI (for complete mining) and Vinacomin's KHCNM proposed for Quang Ninh region.

Table 1: VNIMI and KHCNM functions

Tabela 1: Funkcje VNIMI i KHCNM

X/L	VNIMI	KHCNM
0	1.00	1.00
0.1	0.99	0.97
0.2	0.95	0.89
0.3	0.86	0.74
0.4	0.66	0.55
0.5	0.38	0.32
0.6	0.17	0.16
0.7	0.08	0.08
0.8	0.03	0.03
0.9	0.01	0.01
1.0	0.0	0.0

3.2 Asadi Profile Function

The Asadi profile function is a method that allows predicting vertical displacement in continuous basins for inclined seam mining cases. Asadi proposes determining the displacement basin profile in the case of inclined seam mining by combining two exponential profile functions [14]. The advantage of this prediction function lies not only in its development based on Knothe's theory, which has been widely applied, but also in its theoretical rigor and simplicity in calculation. Another advantage is that it requires minimal observation data; thus it was chosen for testing prediction function construction for Thong Nhat mine as expression (2) [17].

$$\eta_{(s)} = \eta_{max}.\left[c.e^{-6{,}46\left(\frac{-s}{L_1}\right)^{2{,}75}} + d.e^{-4{,}50\left(\frac{s}{L_2}\right)^{1{,}82}}\right] \quad (2)$$

3.3 Accuracy Evaluation of Prediction Results

Prediction accuracy is determined through deviation values (Δ_i) (actual error); mean absolute error (MAE); root mean square error (RMSE); and correlation coefficient (r) between observed subsidence values and predicted values as per formulas (3), (4), (5), and (6).

$$\Delta_i = \eta^p_{(s_i)} - \eta_{(s_i)} \quad (3)$$

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\eta_i - \eta_i^p)^2} \quad (4)$$

$$MAE = \sum_{i=1}^{n}|\eta_i - \eta_i^p|/n \quad (5)$$

$$r = \frac{\sum_{i=1}^{n}(\eta_i - \bar{\eta_i})(\eta_i^p - \overline{\eta_i^p})}{\sqrt{\sum_{i=1}^{n}(\eta_i - \bar{\eta_i})^2 * \sum_{i=1}^{n}\left(\eta_i^p - \overline{\eta_i^p}\right)^2}} \quad (6)$$

where:

- r is correlation coefficient between observed and

predicted values;

- η_i and η_i^p are observed and predicted values respectively;

- $\overline{\eta_i}$ and $\overline{\eta_i^p}$ are mean values of observed and predicted values respectively.

4. Accuracy of Prediction Functions in Mong Duong Coal Mine Conditions

4.1 Characteristics of the Study Area

Mong Duong mine is located in Cam Pha city, Quang Ninh province, about 10 km north of the city center. Studying surface subsidence due to underground mining is particularly important as there are residential areas and many important structures on the mine surface, such as main shafts and shaft houses, auxiliary shafts and shaft houses, ventilation stations, coal conveyors, etc. Observation data used for research purposes were taken from line D located in the second mining face of seam 9 in the northern Mong Duong area. Geological and mining characteristics of the study area are as follows: average seam thickness 2.5 m, average seam dip angle: α = 35 degrees. The mining face started extraction in the second quarter of 2013 and was completely mined by the second quarter of 2014. Observation lines were arranged in two directions: strike and dip, with line D initially consisting of 34 markers, but due to damage during observation, only 25 markers remained. The distance between markers ranged from 10 to 30 m. The elevation of the initial markers was transferred from the state grade IV benchmark at the mine office. Observations were conducted over 2 years with a 2-month cycle. The measuring equipment was a Leica NAK2 level, and the observation work met the requirements of mining surveying standards [18]. The cross-section of observation line D along the dip direction is shown in Figure 4.

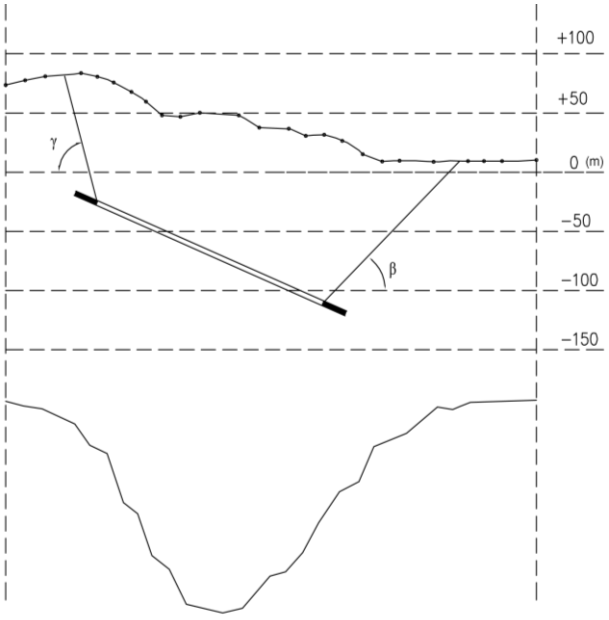

Fig. 4. The cross-section of observation line D along the dip direction at Mong Duong mine

Rys. 4. Przekrój linii obserwacyjnej D wzdłuż kierunku nachylenia w kopalni Mong Duong

4.2 Results

Using prediction functions $S_{(Z)}$ proposed by VNIMI and KHCNM as in Table 1, and Asadi profile function (2) to predict vertical displacement due to underground mining at Mong Duong mine. These prediction results were then compared with observation data to evaluate the accuracy of the proposed methods. Geological-mining parameters include maximum vertical displacement, boundary displacement angle, maximum subsidence angle, displacement basin radius, seam thickness, mining depth, etc., as shown in Table 2 [9].

The Asadi prediction function (2) allows determining the subsidence value of any point on the main cross-section along the dip direction of the seam. Therefore, this function is used to predict the subsidence of all points coinciding with observation points on line D at Mong Duong mine. Prediction accuracy is evaluated based on the actual deviation between predicted subsidence values and observed subsidence values. The results show that the error calculated from the Asadi prediction function (2) and observation results is small. With RMSE = 0.081 m, MAE = 0.055 m, corresponding to 9.9% and 6.7% of the maximum vertical displacement of the displacement basin, respectively. The predicted vertical displacement results of points on line D at Mong Duong mine, as well as the deviation values Δ_i and the RMSE, MAE, r indices, are shown in Table 3.

Prediction Results of Subsidence for Points on Line D at Mong Duong Mine using standard subsidence functions proposed by VNIMI and KHCNM, as in Table 1, and Asadi prediction function (2) to predict vertical displacement due to underground mining at Mong Duong mine. These prediction results were then compared with observation data to evaluate the accuracy of the proposed methods. Geological-mining parameters include maximum vertical displacement, boundary displacement angle, maximum subsidence angle, displacement basin radius, seam thickness, mining depth, etc., as shown in Table 2 [9].

From the results in Table 3, it can be seen that:The Asadi prediction func tion (2) and VNIMI standard subsidence function give relatively similar results. The KHCNM subsidence function gives less accurate results compared to the other two profile functions (RMSE of 0.101 m compared to 0.081 m and 0.080 m; MAE of 0.076 m compared to 0.055 m and 0.059 m). The correlation coefficients of all three methods are quite similar, as shown by the values: r1=0.973; r2=0.985; and r3=0.970, corresponding to the Asadi profile function (2), VNIMI function, and KHCNM function. The comparison chart of RMSE, MAE, and correlation rr errors of the three prediction functions is shown in Figure 5. The correlation chart between observed values and predicted values from the three profile functions is shown in Figure 6. The comparison chart between observed subsidence curves and predicted subsidence curves of the Asadi, VNIMI, and KHCNM functions is shown in Figures 7, 8, and 9, respectively.

Table 2. Geological - Mining Parameters for Line D at Mong Duong Mine

Tabela 2. Parametry geologiczno-górnicze dla linii D w kopalni Mong Duong

Geological - Mining Parameters									
α (độ)	β_o (độ)	γ_o (độ)	θ (độ)	m (m)	L (m)	H (m)	L1 (m)	L2 (m)	η_{max} (m)
25	45	65	60	2,5	190	110	204	261	0,816

Table 3. Prediction Results and Accuracy of Predictions for Line D at Mong Duong Mine

Tabela 3. Wyniki prognoz i dokładność prognoz dla linii D w kopalni Mong Duong

Point name	diference $\eta_{(s_i)}$ (m)	Asadi $\eta^p_{(s_i)}$ (m)	diference Δ_i (m)	VNIMI $\eta^p_{(s_i)}$ (m)	diference Δ_i (m)	KHCNM $\eta^p_{(s_i)}$ (m)	diference Δ_i (m)
D1	0	-0,001	0,001	0	0,000	0	0,000
D2	-0,021	0,000	-0,021	-0,007	-0,014	-0,027	0,006
D3	-0,029	0,000	-0,029	-0,019	-0,010	-0,043	0,014
D4	-0,089	-0,008	-0,081	-0,081	-0,008	-0,080	-0,009
D5	-0,17	-0,026	-0,144	-0,131	-0,039	-0,102	-0,068
D6	-0,203	-0,073	-0,130	-0,253	0,050	-0,142	-0,061
D7	-0,369	-0,164	-0,205	-0,410	0,041	-0,195	-0,174
D8	-0,437	-0,281	-0,156	-0,565	0,128	-0,245	-0,192
D9	-0,594	-0,434	-0,160	-0,668	0,074	-0,367	-0,227
D10	-0,653	-0,605	-0,048	-0,739	0,086	-0,520	-0,133
D11	-0,782	-0,740	-0,042	-0,787	0,005	-0,658	-0,124
D12	-0,816	-0,816	0,000	-0,816	0,000	-0,816	0,000
D13	-0,796	-0,790	-0,006	-0,810	0,014	-0,761	-0,035
D14	-0,673	-0,690	0,017	-0,787	0,114	-0,657	-0,016
D15	-0,656	-0,613	-0,043	-0,756	0,100	-0,567	-0,089
D16	-0,584	-0,524	-0,060	-0,712	0,128	-0,441	-0,143
D17	-0,465	-0,435	-0,030	-0,632	0,167	-0,333	-0,132
D18	-0,351	-0,340	-0,011	-0,520	0,169	-0,231	-0,120
D19	-0,268	-0,261	-0,007	-0,361	0,093	-0,179	-0,089
D20	-0,174	-0,202	0,028	-0,249	0,075	-0,140	-0,034
D21	-0,125	-0,112	-0,013	-0,099	-0,026	-0,088	-0,037
D22	-0,023	-0,058	0,035	-0,038	0,015	-0,058	0,035
D23	-0,034	-0,042	0,008	-0,019	-0,015	-0,046	0,012
D24	-0,006	-0,028	0,022	-0,010	0,004	-0,036	0,030
D25	0	-0,013	0,013	0	0,000	0	0,000
RMSE (m)	0,081			0,080		0,101	
MAE (m)	0,055			0,059		0,076	
r	973			0,985		0,970	

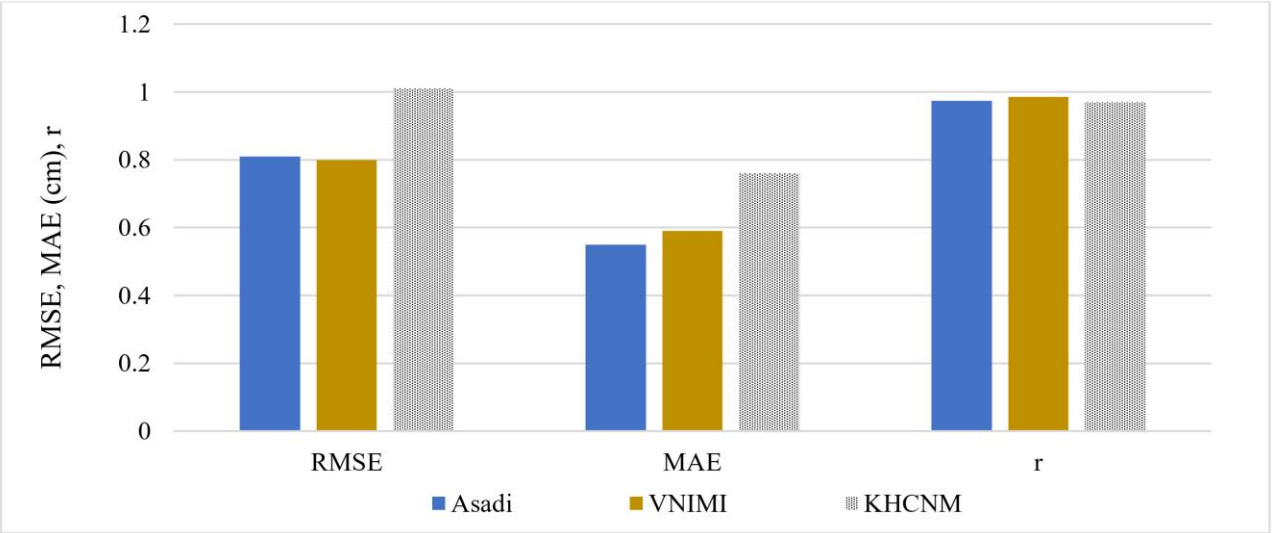

Fig. 5. Comparison chart of RMSE, MAE and correlation r

Rys. 5. Wykres porównujący błędy RMSE, MAE i korelację r

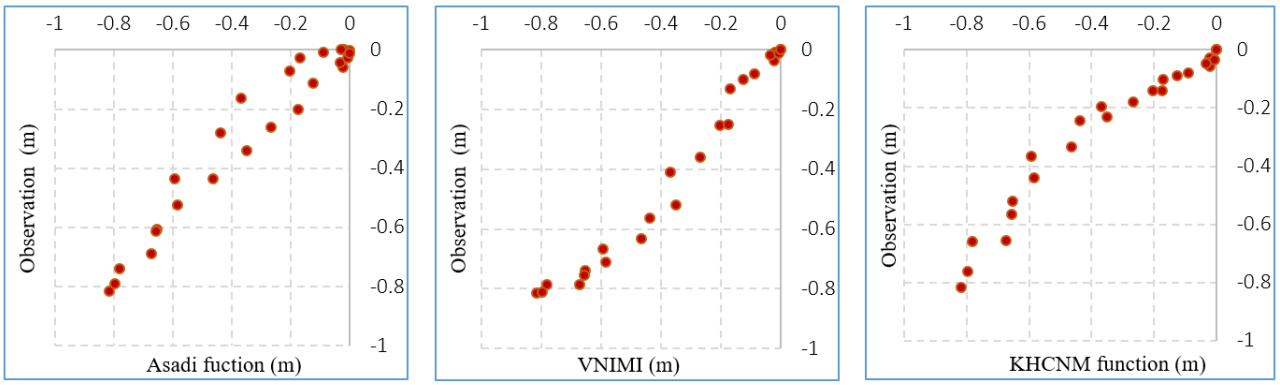

Fig. 6. Correlation chart between predicted and observed values

Rys. 6. Wykres korelacji między wartościami przewidywanymi a obserwowanymi

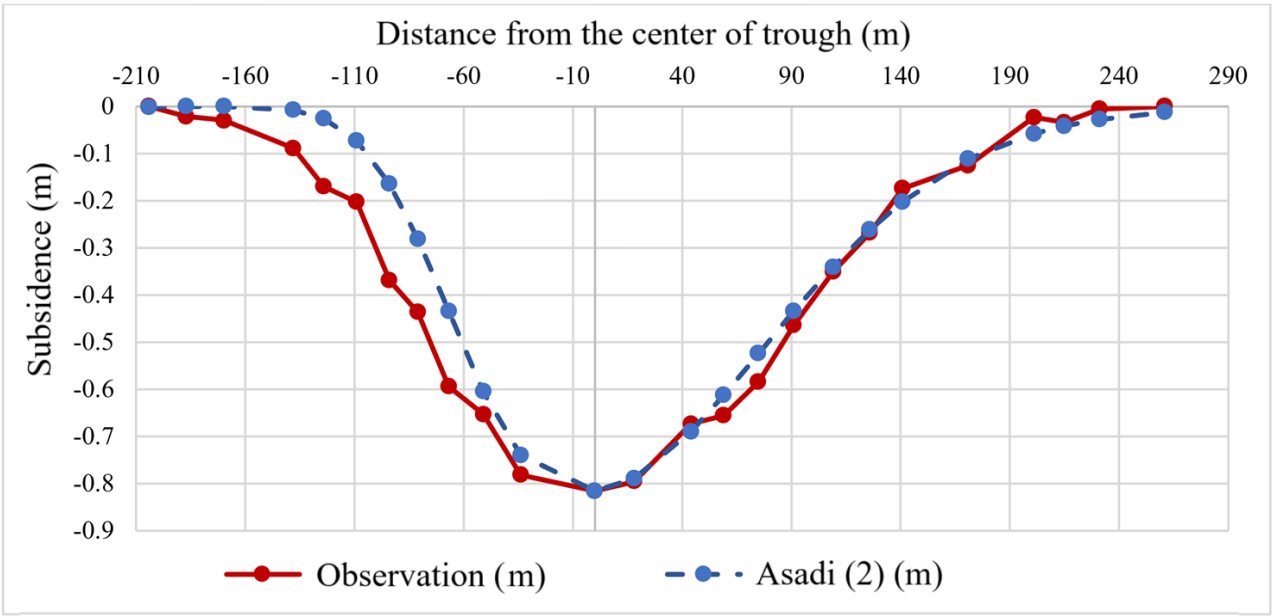

Fig. 7. Comparison of Actual Subsidence Curve and Predicted Curve from Asadi Function (2)

Rys. 7. Porównanie rzeczywistej krzywej osiadania i przewidywanej krzywej z funkcji Asadi (2)

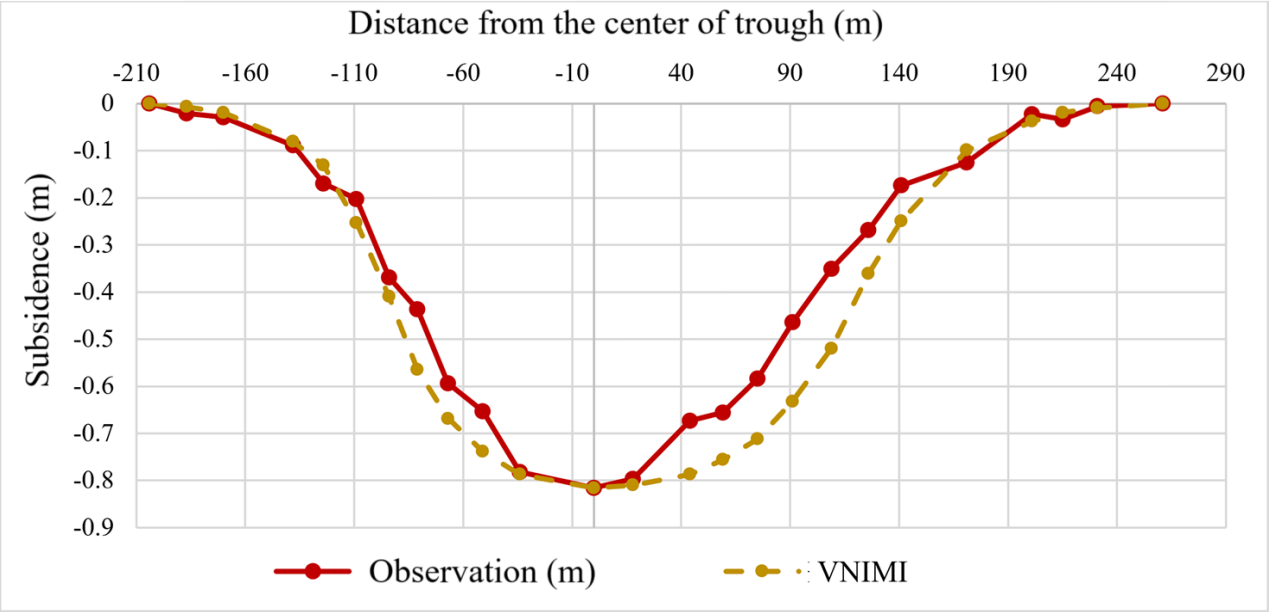

Fig. 8. Comparison of Actual Subsidence Curve and Predicted Curve from VNIMI Function

Rys. 8. Porównanie rzeczywistej krzywej osiadania i przewidywanej krzywej z funkcji VNIMI

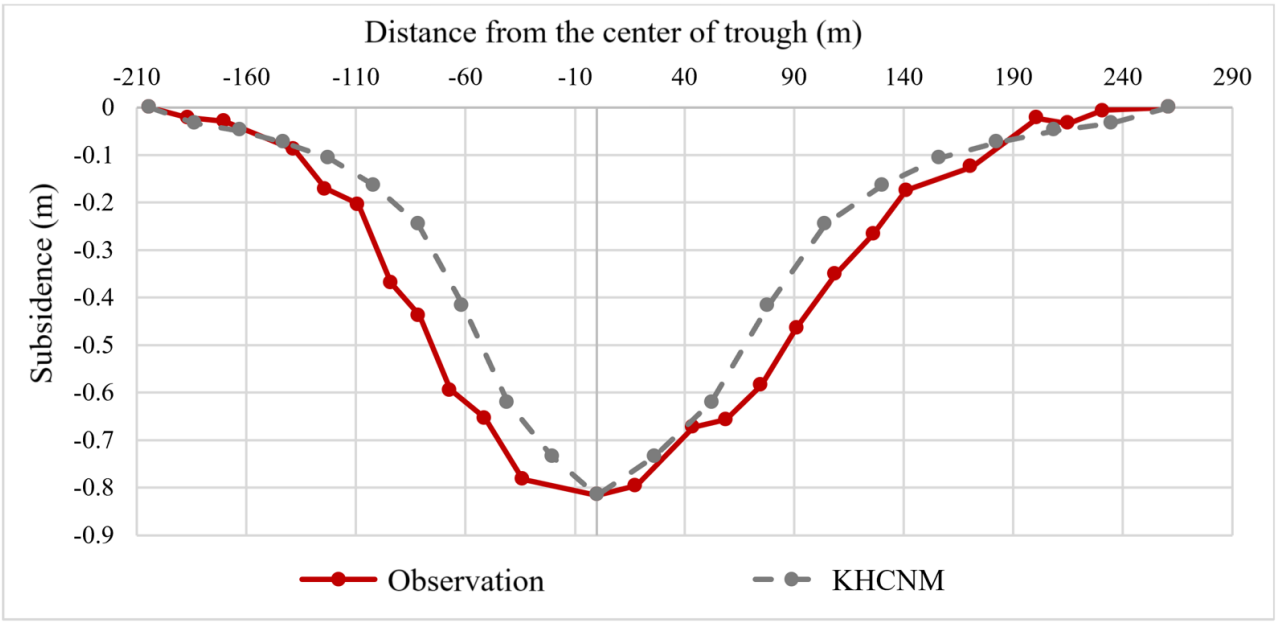

Fig. 9. Comparison of Actual Subsidence Curve and Predicted Curve from KHCNM Function

Rys. 9. Porównanie rzeczywistej krzywej osiadania i przewidywanej krzywej z funkcji KHCNM

5. Conclusion and Recommendations

The research results show that the actual deviation between subsidence values calculated from the Asadi and VNIMI prediction functions and the observed values is very small, confirming the suitability of these functions under the conditions of Mong Duong coal mine.

Based on the accuracy evaluation criteria, including RMSE, MAE, and correlation coefficient r*r*, it is confirmed that the Asadi and VNIMI functions can be applied to predict displacement quantities for coal seams with similar geological and mining conditions.

The Asadi prediction function gives very good results on the right half of the displacement basin cross-section (down-dip side), while the VNIMI prediction function gives better results on the left half (up-dip side).

Displacement deformation due to underground mining is a complex process influenced by many factors. With industrial and urban development, the density of surface structures on the mine increases. Predicting displacement deformation quantities is an important aspect of mining activities. It is recommended to conduct further research combining results from Asadi and VNIMI functions to determine the best subsidence prediction results for the entire displacement basin cross-section.

TYTUŁ: Innowacyjne podejścia do prognozowania osiadania powierzchni w eksploatacji pokładów nachylonych: Porównawcze badanie funkcji Asadi, VNIMI i KHCNM

Niniejsze badanie analizuje dokładność i zastosowalność trzech zaawansowanych metod prognozowania osiadania powierzchni—funkcji profilu Asadi, funkcji osiadania VNIMI oraz funkcji osiadania KHCNM—w trudnych warunkach eksploatacji pokładów nachylonych w kopalni węgla Mong Duong w Wietnamie. Porównując przewidywane wartości osiadania z bezpośrednimi danymi obserwacyjnymi, badanie ocenia precyzję każdej metody za pomocą wskaźników statystycznych, takich jak rzeczywiste odchylenie (Δ), błąd średniokwadratowy (RMSE), średni błąd bezwzględny (MAE) oraz współczynnik korelacji (r). Wyniki pokazują, że zarówno funkcje Asadi, jak i VNIMI wykazują wysoką dokładność, z wartościami RMSE wynoszącymi odpowiednio 0,081 m i 0,080 m oraz wartościami MAE wynoszącymi odpowiednio 0,055 m i 0,059 m. Funkcja KHCNM, choć nieco mniej dokładna, nadal dostarcza cennych informacji z wartościami RMSE i MAE wynoszącymi odpowiednio 0,101 m i 0,076 m. Badanie podkreśla znaczenie precyzyjnego prognozowania osiadania w ochronie struktur powierzchniowych i optymalizacji technologii wydobycia, zalecając dalsze badania w celu integracji zalet funkcji Asadi i VNIMI dla lepszego prognozowania w różnych sekcjach basenu osiadania. Ta kompleksowa ocena oferuje obiecującą ścieżkę do poprawy prognozowania osiadania w eksploatacji pokładów nachylonych, przyczyniając się do bezpieczniejszych i bardziej efektywnych operacji wydobywczych.

Słowa kluczowe: Funkcja profilu, eksploatacja pokładów nachylonych, kopalnia węgla Mong Duong.

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