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Sectional diagram of dynamic subsidence trough at the Mong Duong coal mine: Evaluation and prediction

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ABSTRACT

The main objective of this study is to assess and predict the surface subsidence at the Mong Duong coal mine, Quang Ninh province of Vietnam due to mining activities. For this purpose, a monitoring network for the site was established, and then, the land subsidence data were obtained during the period from 2013 to 2015 with twelve cycles. Two cases were tested. In the first case, the data in the first ten cycles were used. In the second case, seven cycles from the 4th cycle were utilized to establish the parameters of the Knothe time function. Meanwhile, the remaining data were used for the model validation and confirmation of its prediction capability. Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Correlation coefficient (r) and Coefficient of Determination (R^2) were employed to assess the overall performance of the prediction model. The result showed that the model performed well with validation dataset for the second case (RMSE=85 mm, MAE= 61 mm, r=0.977, R^2=0.906). It can be concluded that the Knothe time function model is sufficient if some first cycles are removed when calculating the model parameters.

1. Introduction

Subsidence and its related problems are inevitable consequences of underground mining creating changes to surface landforms, underground water, and surface water (Steve, James, & Kuipers, 2002). It also may damage constructions on the surface as well as in underground mines. Many serious geohazards have been recorded as the result of underground mining in Quang Ninh coalfield. For example, a fan station at 142 m height in the Mao Khe coal mine was totally damaged in 2000 (Institute of Mining Science and Technology, 2008). Some 110 kV electric poles and lines were destroyed; many houses around the Mong Duong coal mine were

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serverly cracked (Institute of Mining Science and Technology, 2011). Hence, mining subsidence prediction is an important task that enables us to reduce mining damages efficiently. Thus, the preliminary objective of mine surveyors is to estimate the impact of underground mining on mine surface. They measure the subsidence of points on mine surface to be able to control the subsidence process and to reduce the damages caused by the underground excavation activity (Kratzsch, 2012).

Many methods and techniques for predicting mining subsidence have been proposed including empirical correlations, profile functions, influence functions, analytical models, and physical models (Reddish & Whittaker, 2012). However, empirical methods have high reliability because they are based on a large number of field measurements. Profile functions are based on a curve fitting procedure that uses mathematical functions to match the measured subsidence profile. When this mathematical function is established by actual field data it can be used for the future prediction of surface subsidence in the mining area (Reddish & Whittaker, 2012). The Knothe time function is one of the most widely used subsidence prediction methods. It was known to be able to describe the whole process of surface subsidence. In the similar mining conditions, the surface subsidence of overlying strata with smaller c values takes longer time to stabilize than that with larger c (Hu et al., 2015). There are many methods to determine the parameter c of the model. Based on the angle of full subsidence, a new model was proposed for determining the parameters of the Knothe time function, and the physical meaning of each variable is clear and easily obtained (Hu et al., 2015).

In the Quang Ninh coal basin, field observation has demonstrated that the subsidence starts occurring with some initial delays. In other words, at beginning the subsidence is relatively small since it takes time to propagate the subsidence up to the surface. It increases with time until reaches the maximum value (Long, My, & Luyen, 2016). The maximum subsidence velocity often is observed in the second year after the excavation implementation. In some mines, the maximum subsidence velocity is observed in the first few months after excavation. In other cases, the maximum subsidence velocity is observed in the third or even the fourth year. For properly monitoring surface subsidence, apart from registration, it is necessary to check the earlier prediction. The underground coal mines of the Mong Duong mine has caused ecological problems, especially problems related to mining damages and received much attention from research community and the public. Hence, the main objective of this article is to assess and predict the surface subsidence from measurements conducted in this area.

2. Research Method

2.1. The Knothe time function

To describe surface subsidence over time caused by underground mining, Knothe analyzed a large number of surveying data and found that the relationship between subsidence of a surface point and time was obtained by using Equation (1) (Knothe, 1953).

$$\mathrm{W}(t_i) = \mathrm{W}_0(1 - e^{-ct_i}) \tag{1}$$

where W_0 is total value of subsidence at time t; c is time coefficient; t_i is time of i^{th} cycle monitoring from the first cycle.

2.2. Determining the parameters of the Knothe time function

It can be observed that when t = ∞ then $W_\infty = W_0 = W_{max}$. For given values of W_k and c, we can predict W_{ti} for any surface point.

The values of W_k and c can be determined based on the subsidence observed points. If the number of observation cycles is greater than one, W_0 and c can be determined by the least squares principle method. Error equations can be

$$V_i = W_0(1-e^{-c.t_i}) - W_{t_i} \quad (2)$$

If the subsidence values are observed with the same accuracy, W_0 and c are solved with the least square [VV] = min. The approximate value of W_0 is assigned by subsidence value of the last cycle and the approximate value of c (c0) is assigned by 0.1.

Equation (2) can be expanded by a linear transformation as (Chinh, 1997)

$$V_i = A_i.dw + B_i.dc - L_i \quad (3)$$

where

$$A_i = (1-e^{-c_0 t_i})$$
$$B_i = W_0.t_i e^{-c_0 t_i} \quad (4)$$
$$L_i = W_{t_i} - W_0(1-e^{-c_0 t_i})$$

Equation (3) can be expressed by matrix form as

$$V = A.X - L \quad (5)$$

where,

$$V = \begin{bmatrix} V_1 \\ V_2 \\ \dots \\ V_n \end{bmatrix} \quad A = \begin{bmatrix} A_1 & B_1 \\ A_2 & B_2 \\ \dots & \dots \\ A_n & B_n \end{bmatrix}$$
$$X = \begin{bmatrix} d\eta \\ dc \end{bmatrix} \quad L = \begin{bmatrix} L_1 \\ L_2 \\ \dots \\ L_n \end{bmatrix} \quad (6)$$

The system of normal equations is

$$A^T AX = A^T L \quad (7)$$

Solving the system of normal equations to obtain vector X. The best probability values of W and c are calculated as

$$W = W_0 + d_w$$
$$c = c_0 + d_c \quad (8)$$

The parameters W_0 and c show the rule of subsidence process, the subsidence of points at the time $t_k = t_n + \Delta t$ can be predicted (t_n is the time at the last monitoring cycle). Subsidence value at t_k is computed as

$$W_{t_k} = W_k(1-e^{-ct_k}) \quad (9)$$

2.3. Performance assessment

After determining the parameters of the subsidence point for the prediction model, equation (1) can be used for subsidence prediction of the point in the next cycle. Then the result is compared with the actual monitored values. The relevance of points subsidence prediction model over time are evaluated by the Root mean square error (RMSE), Mean absolute error (MAE). The accuracy of the subsidence lines is evaluated by RMSE, MAE, Correlation coefficient (r) and Determination coefficient R^2 between the predicted lines and the monitored lines. The lower the RMSE and the MAE, and the higher the r and R^2 show the better model is.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(w_{t_k} - w_{t_k}^{p})^2} \quad (10)$$

$$\text{MAE} = \sum_{k=1}^{n}\left|w_{t_k} - w_{t_k}^{p}\right|/n \quad (11)$$

$$r = \frac{\sum_{k=1}^{n}(w_{t_k} - \bar{w})(w_{t_k}^{p} - \overline{w^p})}{\sqrt{\sum_{i=1}^{n}(w_{t_k} - \bar{w})^2 * \sum_{i=1}^{n}\left(w_{t_k}^{p} - \overline{w^p}\right)^2}} \quad (12)$$

$$R^2 = 1 - \frac{\sum_{k=1}^{n}(w_{t_k} - w_{t_k}^{p})^2}{\sum_{k=1}^{n}(w_{t_k} - \bar{w})^2} \quad (13)$$

where r is correlation coefficient; w_{t_k} and $w_{t_k}^{p}$ are measured and predicted values at t_k; $\bar{w}$ and $\overline{w^p}$ represent correspondent medium values, respectively.

3. Application for Mong Duong Coal Mine

The experimental data were collected on North Mong Duong area, Mong Duong mine, from 2 observation lines. Line D is established along the dip direction and line P in the strike direction of excavated chamber. 12 measurement cycles were carried out using Leica NAK2 automatic level. The interval between two cycles is approximately 2 months. Measuremet precision satisfied the Vietnam National Specifications on mine surveying (closed loop leveling less than $20\sqrt{L}$ (mm) (Ministry of Information & Communications, 2013).

To verify the Knothe function in underground mining of the Mong Duong coal

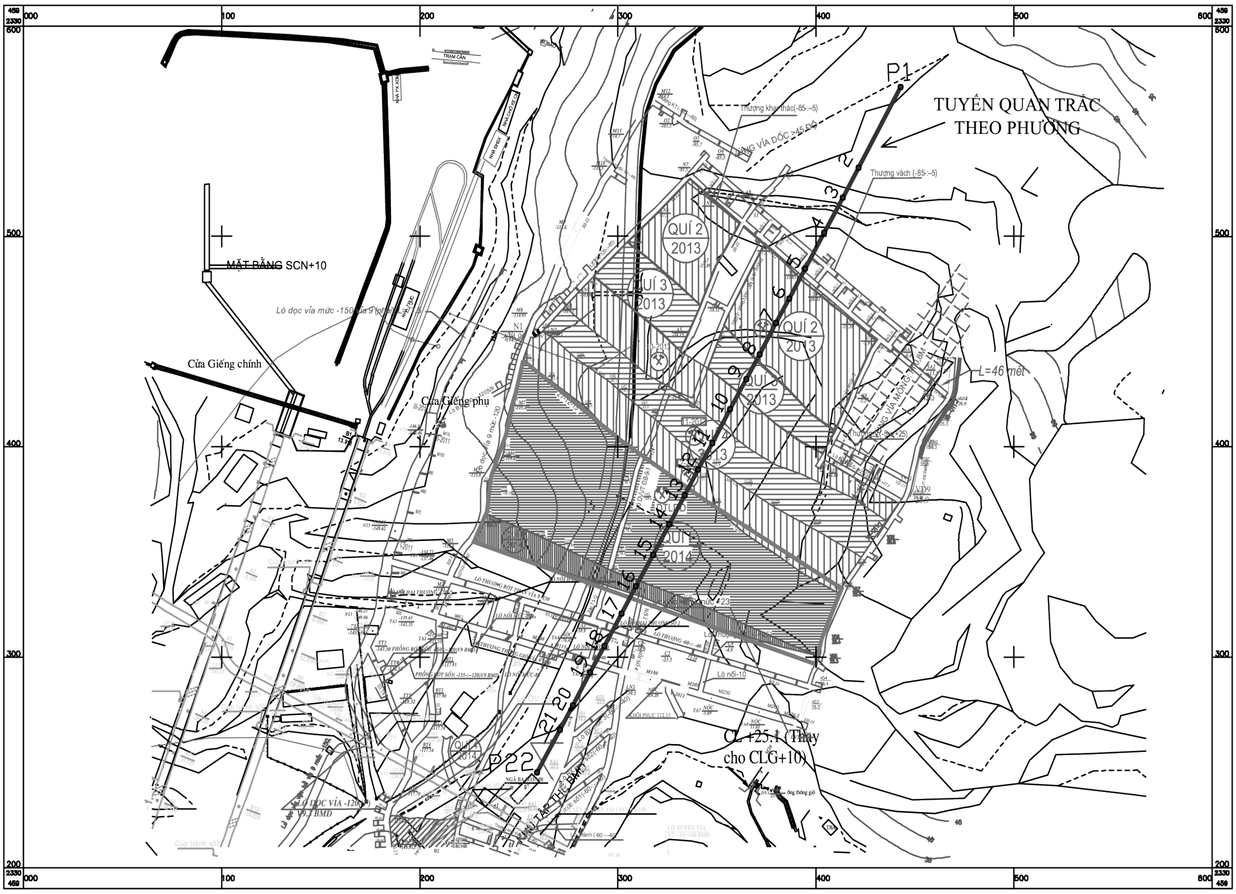


Figure 1. Study are and the line P, Mong Duong coal mine

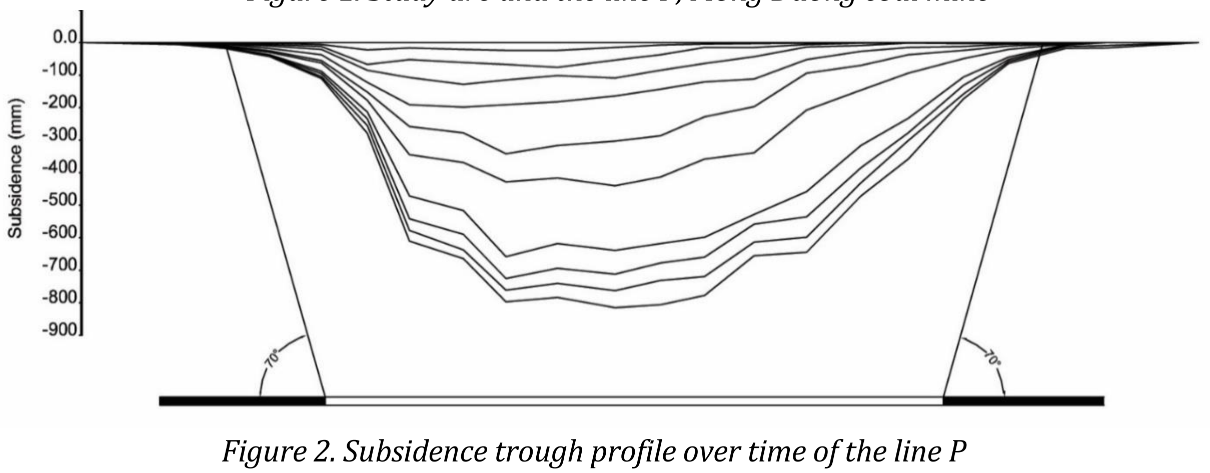


Figure 2. Subsidence trough profile over time of the line P

mine, all leveling data in 12 cycles for 17 points out of 22 points in the line P were used in Table 1. Figure 1 showing study area with the line P. Subsidence profile of the line P with time is shown in Figure 2. W_k and c were then calculated from observed results.

4. Results and discussion

4.1. Building prediction models

Case 1: Mornitoring subsidence data of the first 10 cycles (from 0th month to 18th month) of 16 points in the line P were used to build subsidence models. The method introduced in Section 2 was used to determine W_k and c for all 16 points. The calculated values of parameters were used as the inputs for Equation (1) to recalculate the subsidence of all points in the first 10 cycles.

Table 1. Leveling measurement (mm)

Point ID	Cycles											
	1	2	3	4	5	6	7	8	9	10	11	12
P3	0	-1	-2	-3	-5	-9	-12	-14	-15	-17	-18	-18
P4	0	-2	-6	-11	-18	-26	-30	-35	-37	-40	-42	-43
P5	0	-7	-12	-21	-38	-55	-63	-71	-89	-96	-105	-111
P6	0	-23	-67	-85	-123	-153	-178	-195	-213	-235	-256	-279
P7	0	-17	-52	-108	-192	-258	-345	-412	-472	-541	-578	-610
P8	0	-22	-62	-129	-198	-278	-369	-452	-516	-589	-637	-664
P9	0	-25	-67	-115	-192	-342	-429	-558	-658	-725	-761	-797
P10	0	-24	-77	-102	-183	-317	-416	-547	-617	-694	-740	-783
P11	0	-15	-54	-109	-165	-303	-441	-569	-639	-711	-762	-814
P12	0	-8	-37	-86	-144	-287	-414	-528	-618	-677	-731	-805
P13	0	-5	-16	-64	-121	-229	-358	-506	-598	-659	-719	-777
P14	0	-4	-15	-43	-113	-197	-339	-452	-528	-558	-613	-655
P15	0	-2	-6	-14	-53	-94	-207	-336	-458	-535	-598	-644
P16	0	-1	-2	-9	-27	-70	-147	-216	-316	-385	-432	-471
P17	0	0	-1	-2	-15	-38	-95	-155	-233	-278	-302	-359
P18	0	-2	-3	-4	-12	-24	-49	-79	-107	-132	-158	-173
P19	0	-1	-2	-4	-5	-11	-22	-27	-45	-53	-59	-64
P20	0	0	0	-2	-3	-4	-5	-4	-6	-8	-12	-18

The accuracy of the prediction models with its RMSE, MAE error for each point over time, are presented in Table 2. Realizing that the RMSE và MAE of points over time quite large, the causes can be explained as the whole development process of the subsidence with time can be divided into four stages: initial subsidence stage, accelerated subsidence stage, stable subsidence stage and last subsidence stage. During the first stage, the velocity of subsidence is very low with the subsidence increasing from "0" with time slowly. During the second stage, the velocity of subsidence increases up with time, and the subsidence increases with time quickly. During the third stage, the velocity of subsidence decreases with time. During the fourth stage, the velocity of subsidence continues to decrease and finally tends to be zero. (Edward & Gren, 1990; Liu, Wang, Guo, Yuan, & Li, 2013).

Case 2: Removing three first monitoring cycles, only observational data from the 4th to the 10th cycles were used to build predictive models. The RMSE, MAE of the prediction models for each point over time, are presented in Table 2. The difference subsidence curves between cases 1 and 2 for example point 9 are shown in Figures 3a and 3b. It is obvious that the precision of the case 2 is better than the case 1.

Table 2. The accuracy of the prediction models for each point over time (mm)

Point ID	RMSE		MAE	
	Case 1	Case 2	Case 1	Case 2
P3	3	1	1	1
P4	5	4	1	1
P5	15	10	5	4
P6	25	33	9	12
P7	92	49	31	26
P8	100	57	33	32
P9	130	59	37	35
P10	129	60	38	38
P11	132	47	49	26
P12	148	73	46	45
P13	158	85	48	49
P14	132	63	36	33
P15	158	121	50	68
P16	118	97	39	57
P17	90	78	29	44
P18	43	36	15	21
P19	15	12	5	7

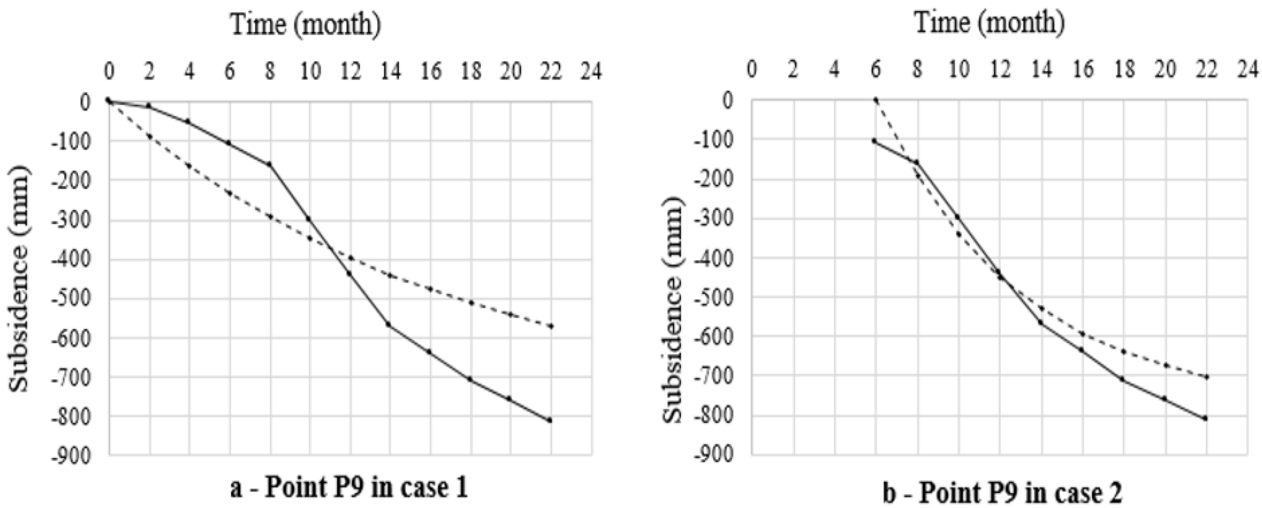
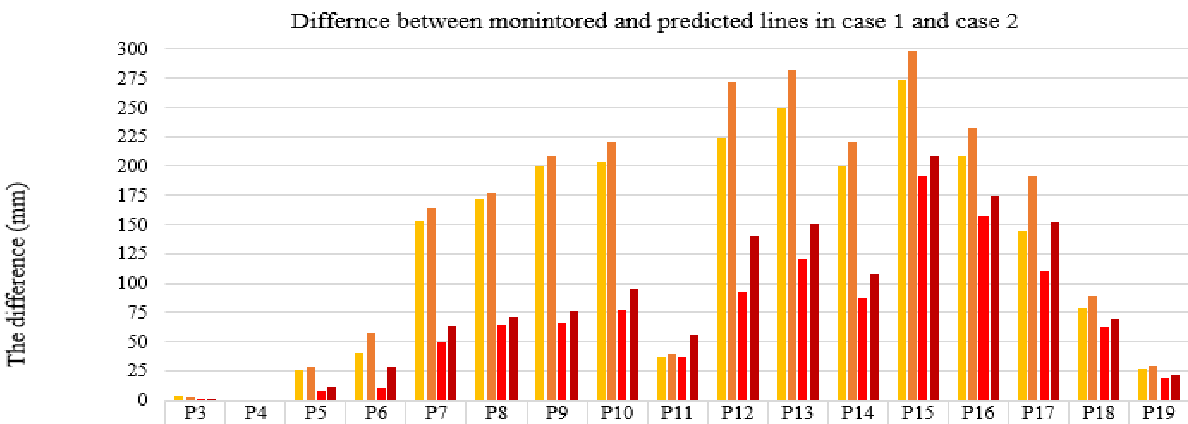


Figure 3. a. Subsidence of point 9 in case 1; b. Subsidence of the point 9 in case 2



	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19
Cycles 11 (case 1)	4	-1	25	41	153	172	200	203	37	224	249	199	273	208	144	79	26
Cycles 12 (case 1)	3	-1	28	57	165	177	209	220	39	272	282	220	299	233	191	89	29
Cycles 11 (case 2)	1	-1	8	10	49	64	66	77	37	92	121	87	191	157	110	62	20
Cycles 12 (case 2)	1	0	12	28	63	71	76	95	56	141	151	107	209	175	152	70	22

Figure 4. The difference between predicted and measured values in the 11th and 12th cycles

Table 4. Precision of the line P curves prediction

	Case 1		Case 2	
	Cycle 11th	Cycle 12th	Cycle 11th	Cycle 12th
RMSE	160	179	85	101
MAE	131	148	61	76
r	0.957	0.962	0.977	0.974
R^2	0.626	0.664	0.906	0.875

4.2. Models assessment

The models of booth cases were used to predict the subsidence of 17 above points at the 11th and 12th cycles (20th month and 22th month). The difference of predicting and mornitoring values is shown in Figure 4. At a single measuring point, what can be obtained is the curve of point movement over time. At the measuring line, on the other hand, what can be obtained is a sectional diagram of trough deformation (Kratzsch, 2012). So, the above predicted subsidence of idividual point at the same cycles were used to obtained the predicted subsidence lines. RMSE, MAE, R and R^2, as presented in Table 4, show that the second case gives a better predicted results than the first case. The predicted subsidence line curves and the actual line curves are shown in Figure 5 and Figure 6. Hence, it can be concluded that the results calculated from the Knothe time function is closer to actual observations when removing some first cycles to build the model.

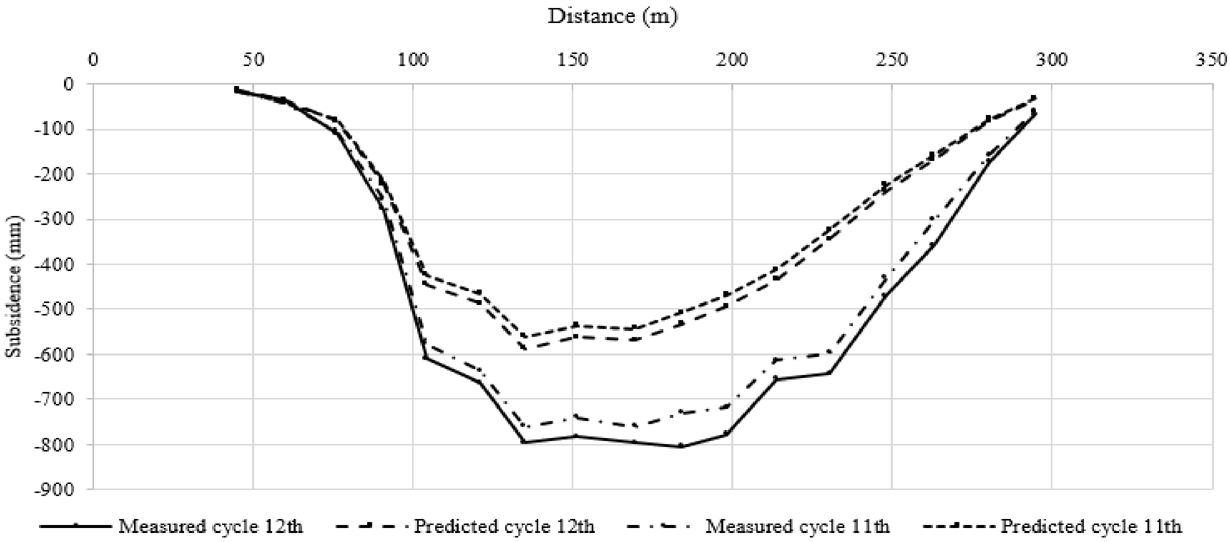


Figure 5. Subsidence scheme of measured and predicted in case 1

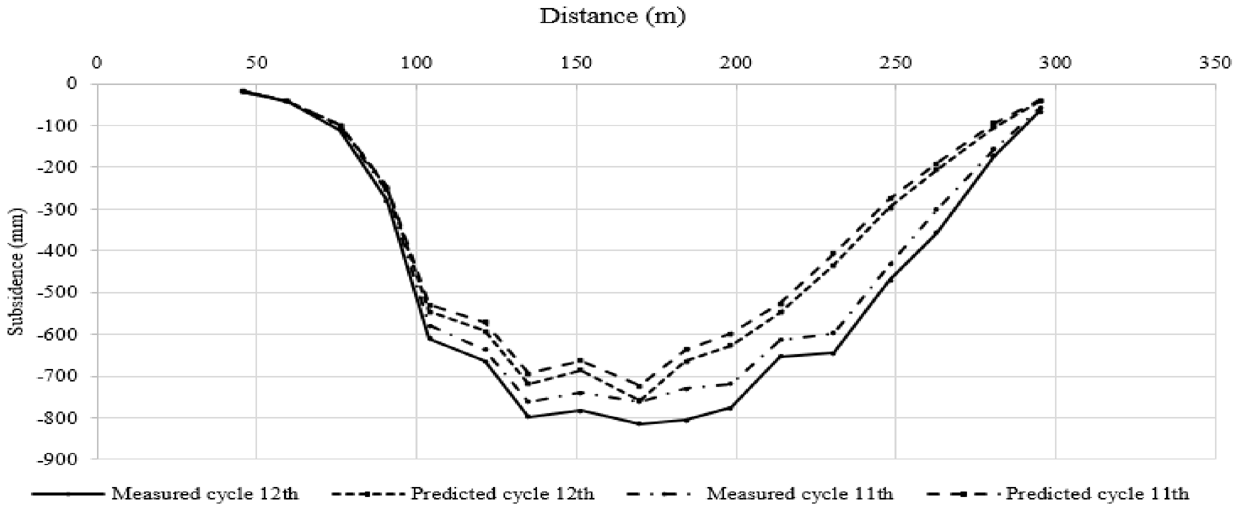


Figure 6. Subsidence scheme of measured and predicted in case 2

5. Conclusions

The applicability of the Knothe time function for surface subsidence prediction was validated with measuring points in the Mong Duong coal mine. It is found that if the whole observation cycles are used to build predictive models, the expected results are less accurate than the case of removing some of the first cycles because it takes a period of time to spread the movement from underground up to surface.

When building a prediction model, the most important point is to determine approximate initial values. When the initial values are close to the real values, the computation will quickly reach a converge. The approximate value of W_0 should be selected by the last monitoring settlement cycles, while the approximate value of c_0 should be equal to average values c_i calculated from two consecutive monitoring cycles.

The Knothe time function should be used to determine the shape of the profile of dynamic subsidence trough to provide the effecient protection method for constructions on the mine surface, ensuring the safety of excavation and reducing the associated risks. For further study, more advanced subsidence models should be considered.

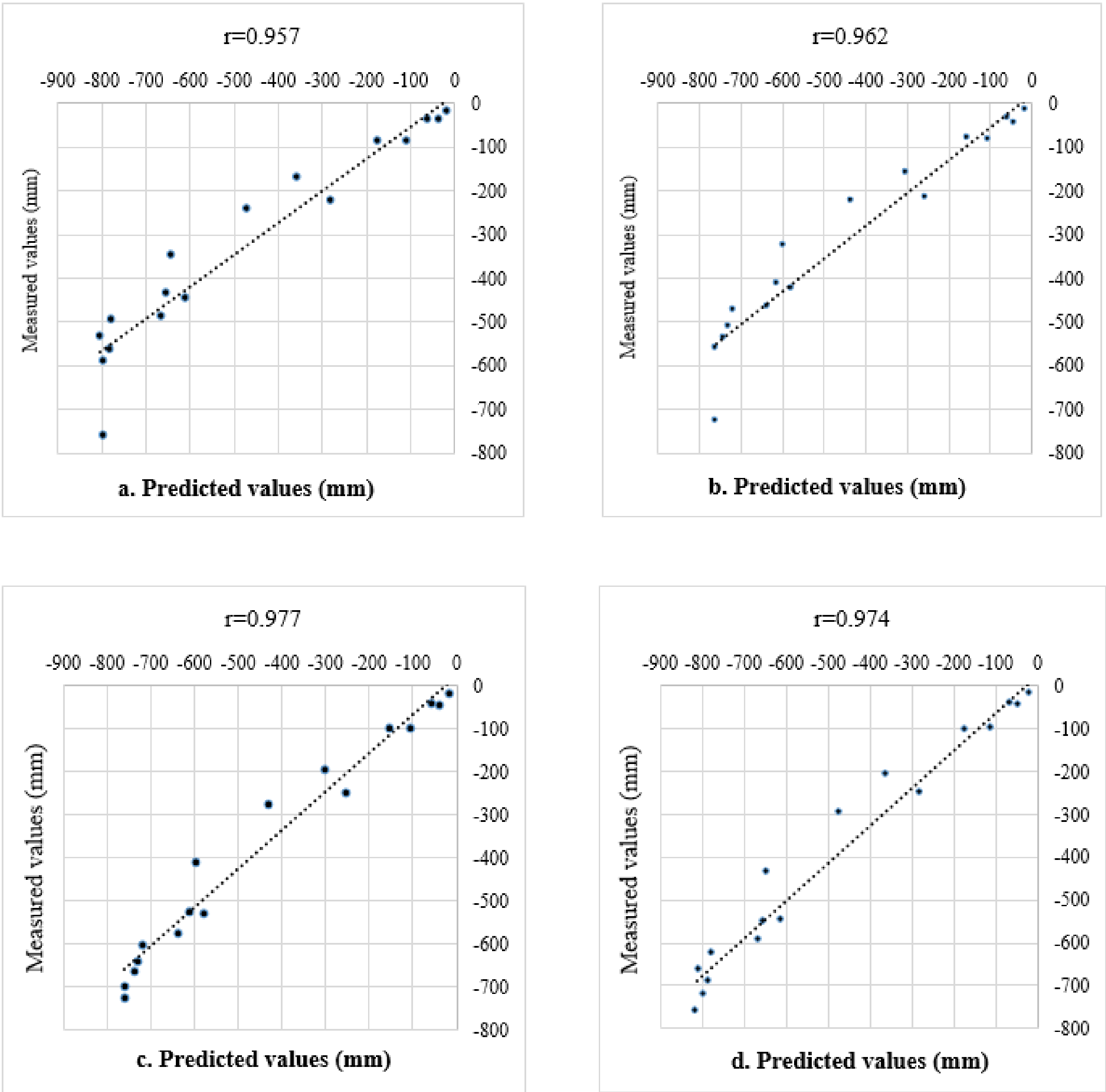


Figure 7. a. Case 1: Correlation between the measured and predicted of the line P in the cycle 11th
b. Case 1: Correlation between the measured and predicted of the line P in the cycle 12th
c. Case 2: Correlation between the measured and predicted of the line P in the cycle 11th
d. Case 2: Correlation between the measured and predicted of the line P in the cycle 12th

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