Development of a new mathematical model for prediction of surface subsidence due to inclined coal-seam mining

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Synopsis

Subsidence phenomenon as an unwanted consequence of underground mining can cause problems for environment and surface structures in mine area. Surface subsidence prediction for inclined and steep seams has been given less attention than horizontal seams due to the difficulties involved in the extraction of such coal-seams. This paper introduces a new profile function method for prediction of surface subsidence due to inclined coal-seam mining. The results of calculation with the new function indicate that the predicted value has good agreement with the measured data.

Keywords: subsidence; coalmining; caving mining methods; longwall mining; profile function.

Introduction

Increasing world demand for energy and mineral resources has resulted in much mechanization and rapid excavation techniques by modern mining operations[1]. Exploitation of minerals using caving methods such as the longwall mining method will result in surface subsidence. This phenomenon can cause environmental problems and damage to surface and subsurface structures[2–6].In order to protect the environment and structures from these damages, precise subsidence prediction is essential. When a horizontal seam is mined, the subsidence trough has symmetric shape, whereas in inclined seams it is non-symmetric and complicates the prediction of the surface subsidence profile[7,8].

In some countries, large volumes of coal reserves of high quality are classified as inclined and steep strata. For economic reasons, these deposits have to be extracted and, consequently, the problems of surface subsidence of these types of deposits are still highly relevant.

During the last decades, several new models of subsidence prediction for level, inclined, and steep seams have been developed worldwide[9–14]. Still, there are some complexities in the prediction of subsidence profiles in inclined and steep seam mining.

Subsidence prediction methods

Subsidence prediction methods can be classified into six categories:

Theoretical, profile function, influence function, graphical, physical, and numerical modelling[15].

Theoretical methods, which are mainly established on continuum mechanics principles, try to explain a mechanism that can predict the magnitude of subsidence. To achieve this, many behavioral models for immediate roof and strata above it, such as elastic, plastic, visco-elastic, and elasto-plastic ones, have been selected to predict the surface subsidence. Szpetowski presented a theoretical model based on the stochastic model for calculation of surface subsidence at point P(x, y) when excavating an area having coordinates of *a*, *b*, *c*, and *d* as shown in Figure 1, at a depth of *H* and thickness of *m* as below[16]:

$$S = \frac{a \cdot m}{4\pi BH}\int_a^b \exp\left[-\frac{(x-\xi)}{4BH}d\xi\right] \times \int_c^d \exp\left[-\frac{(y-\eta)^2}{4BH}\right]d\eta \qquad [1]$$

where *a* is the subsidence factor, symbols ξ and η are coefficients of the working conditions, and *B* can be calculated from

$$\frac{1}{\sqrt{2B}} = \frac{k\sqrt{2\pi}}{1000} \qquad [2]$$

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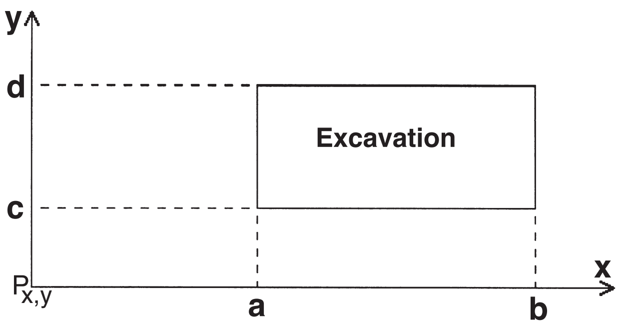

Figure 1—Location of point *P* and excavation[16]

where k is a characteristic quantity of the overburden strata.

In the profile function method, a number of standard functions is defined to predict the magnitude of subsidence. Some of them are in the form of negative exponential functions, and hyperbolic tangent functions. These functions contain some site-specific parameters that have to be selected very carefully according to site conditions. For this reason different standard functions have been suggested for different coalfields in America, England, Russia, Japan, and some other countries. This method can be used for square or other simple geometrical shapes of stopes. For example, tangent hyperbolic kinds of profile function that were proposed by Karmis *et al.* to predict subsidence in the Appalachian coalfield in USA in 1984 is[17]:

$$S(x) = \frac{S_O}{2}\left(1 - \tan h\left(\frac{cx}{B}\right)\right) \qquad [3]$$

where S_O is the maximum subsidence in the subsidence profile; x is horizontal distance from the origin, which is located at the centre of the subsidence profile; B is distance from the influence point to the centre of the profile; and c is a site-specific coefficient that is 1.4 for subcritical and 1.8 for critical and supercritical panels in a monitored coalfield.

The influence function method is based on the effect of the extraction of infinitesimal elements of an area. Subsidence at any point on the surface is obtained from the sum of the influence of each extracted element. With increasing distance, the effectiveness of an element decreases on subsidence and in a far enough distance its effect decreases to zero. This method can be used for prediction of subsidence in very different shaped extracted areas. Methods such as probability function and zone area fall into this category. For example, Huayang *et al.* have been presented a seam dip angle based on a mining subsidence model as below[10]:

$$W_{eh}(x,y) = \frac{\cos a}{r_h^2} e^{-\pi\left(x^2+\left(y-H\cdot\cot\theta_o\right)^2\right)/r_h^2} \qquad [4]$$

$$W_{ev}(x,y) = \frac{\sin a}{r_v^2} e^{-\pi\left(x^2+\left(y-H\cdot\cot\theta_o\right)^2\right)/r_v^2} \qquad [5]$$

where $W_{eh}(x,y)$ and $W_{ev}(x,y)$ are mining subsidence basins of vectors dS_h and dS_v respectively, dS_h and dS_v are horizontal and vertical elements of subsidence vector d_S, ($\vec{dS} = \vec{dS}_h + \vec{dS}_v$), r_h and r_v are the main influence radii of mining of flat and vertical seams respectively, H is mining depth of dS at point P and θ_0 is the mining influence propagation angle.

In the empirical method, different graphs and tables are given for different conditions and geometrical shapes. It is possible to predict the amount of subsidence using these graphs and tables. The National Coal Board (NCB) has suggested one of the most well-known graphs for the prediction of subsidence. For example, a graph for the prediction of surface subsidence in horizontal stopes is given in Figure 2.

In the physical method, by combining different materials such as sand and gelatin, a real model, but smaller than the extracted area, has been built. By precise monitoring and processing of data, the amount of subsidence in a real condition is calculated[18]. An example of the physical model is given in Figure 3.

In numerical methods, displacements and subsidence of ground surface can be calculated by using finite elements, boundary elements, distinct elements, and finite difference methods. Application of a computer for solving very complex

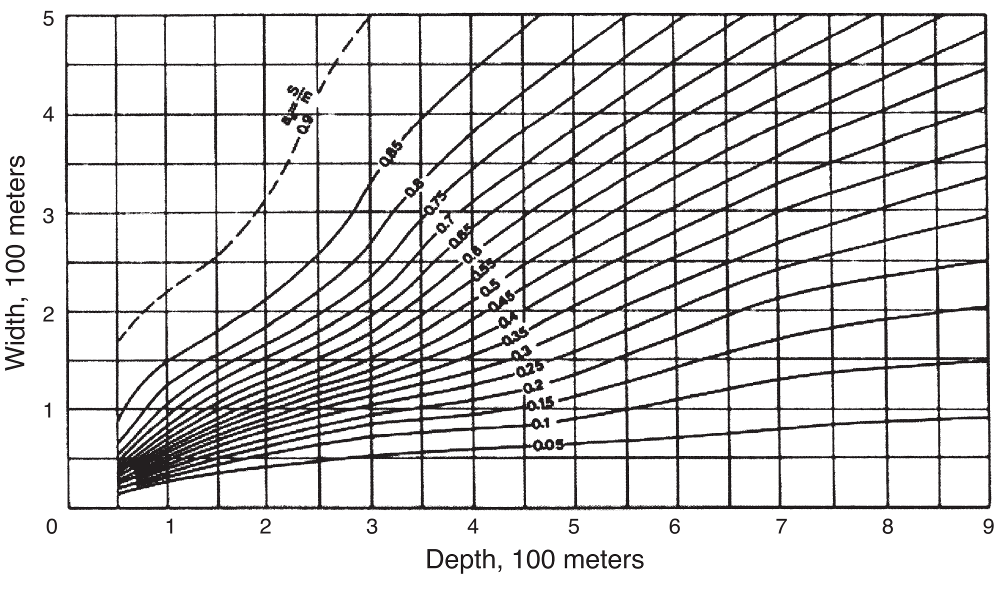

Figure 2—Graph suggested by NCB[14]

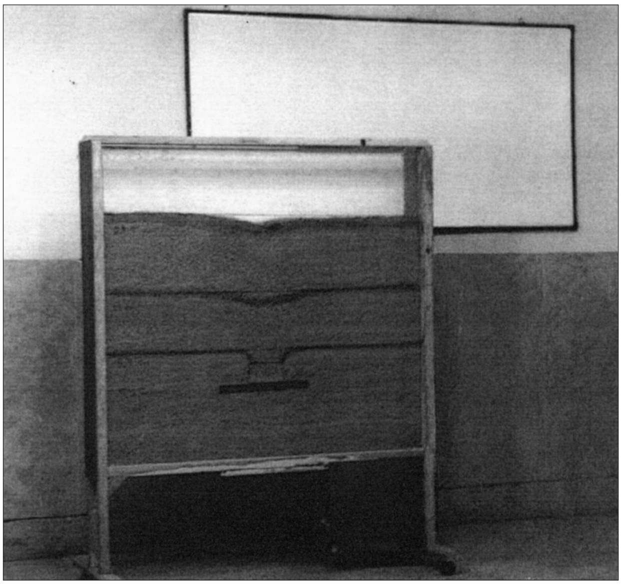

Figure 3—A physical model for prediction of subsidence[17]

equations in diverse initial and boundary conditions with different material behaviour made numerical methods more popular in the prediction of subsidence. In this regard, different software has been developed to consider inhomogeneous and anisotropic behaviour of rock mass worldwide[19].

Difference between subsidence profiles in horizontal and inclined seams

The vertical cross-sections of the subsidence trough along the strike and normal to the strike of the seam passing through the point of maximum surface subsidence are called the principal cross-sections of the subsidence trough. In this paper, all of the subsidence profiles are along the major sections. If the coal seam is horizontal then the surface subsidence profile has a symmetric shape in section. However, it is non-symmetric, if the coal-seam is inclined, as shown in Figure 4.

The proposed new model

The new model is considered for prediction of the surface subsidence profile due to inclined coal-seams with regard to longwall mining. In this condition, the subsidence profile is asymmetric in shape and has been divided into two parts, one up dip and another down dip. The point of maximum subsidence in the profile is the boundary of two parts.

Two specific profile functions have been developed for prediction of surface subsidence in both parts of the subsidence profile, which are combined with each other by a conditional function as shown below[20]:

$$S(x) = S_{\max}\left[c \cdot e^{-f\left(\frac{-x}{R_1}\right)^g} + d \cdot e^{-p\left(\frac{x}{R_2}\right)^q}\right] \qquad [6]$$

where $S(x)$ is subsidence at point P, x is the horizontal distance of the point P to the location where the subsidence profile presents maximum value (negative values of x for up-dip and positive values for down-dip side of the panel), and f, g, p, and q are profile constants obtained from field studies.

Other parameters in the formula are calculated as follows:

$$S_{\max} = m \cdot a \cdot cas\alpha \qquad [7]$$

$$R_1 = h\tan(\beta u) + 0.5l\cos(\alpha) + (h + 0.5l\sin(\alpha))\tan(\theta) \qquad [8]$$

$$R_2 = 0.5l\cos(\alpha) - (h + 0.5l\sin(\alpha))\tan(\theta)) + (h + l\sin(\alpha))\tan(\beta l) \qquad [9]$$

$$c = -0.5(sign(x) - 1) \qquad [10]$$

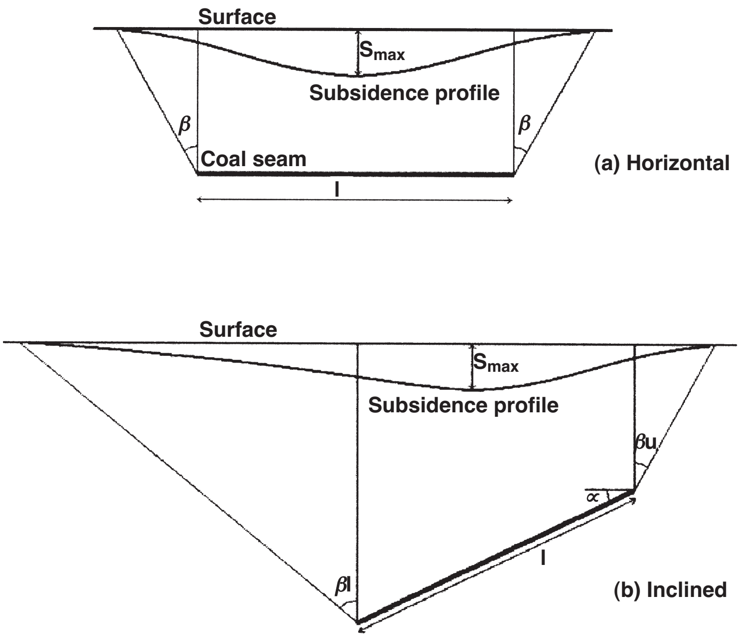

Figure 4—Subsidence profile in horizontal and inclined coal-seams

$$d = 0.5\left(sign(x) + 1\right) \quad [11]$$

where m is the seam thickness, a is the subsidence factor, α is seam dip angle, R_1 and R_2 are subsidence magnitude in the up-dip and down-dip sides of the trough, respectively, h is the depth of workings in the up-dip side of the panel, βu is the angle of draw in the up-dip side of the panel, βl is the angle of draw in the down side of the panel, l is the working width, θ is the trough angle, c and d are condition coefficients, and $sign(x)$ is the sign function as follows.

$$\begin{cases} When\ x < 0 \Rightarrow sign(x) = -1,\ c = 1 \text{ and } d = 0 \\ When\ x = 0 \Rightarrow sign(x) = 0,\ c = 0.5 \text{ and } d = 0.5 \\ When\ x > 0 \Rightarrow sign(x) = 1,\ c = 0 \text{ and } d = 1 \end{cases}$$

Some of mentioned parameters are shown in Figure 5.

Verification of model

The new model is verified with the observed surface subsidence data from the Negin coalmine in the Tabas region, which is located in the eastern part of Iran. This region is one of the most important coal regions in Iran. The Tabas region contains three areas named Parvade, Mazino, and Nayband. Figure 6 shows these areas.

Negin is one of the biggest coalmines in the Parvade area. Exploitation is confined to the completely caving longwall mining method. Table I summarizes the mining conditions.

In this area, coal-seams are inclined. Figure 7 shows a stratigraphic column over the seam C1 in the Negin coalmine area.

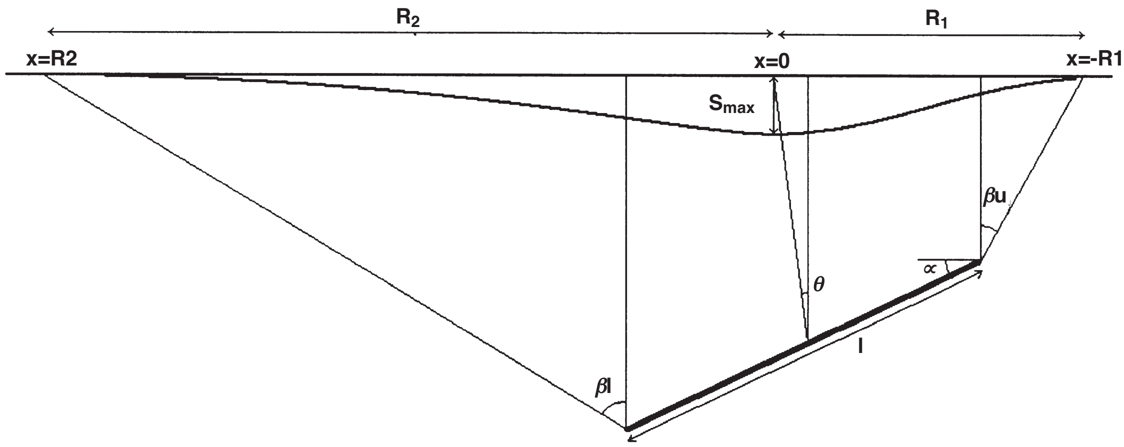

Figure 5—Some parameters in the new model

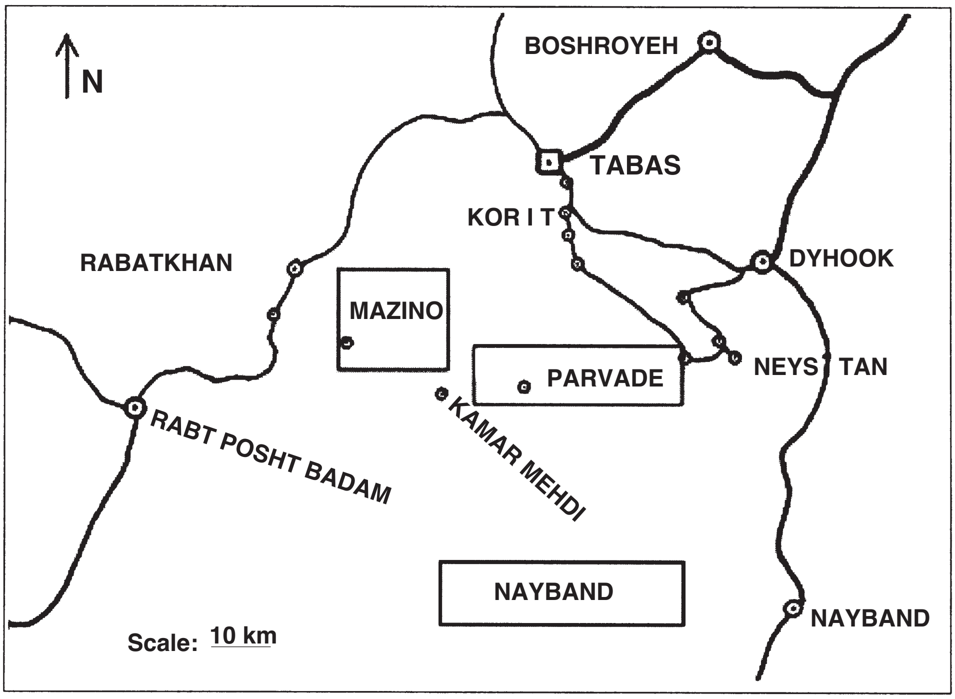

Figure 6—Three areas in Tabas region

At Negin coalmine, three subsidence observation lines with 69 stations were laid out in the direction of the dip of seam C1. In this study, subsidence has been measured after three years of mining by using the survey method. Figure 8 shows the location of observation lines in the mine area.

Table I

Mining conditions in Negin

Parameter	Value
Seam dip angle	29.5°
Seam thickness	1.8 m
Working length	95 m
Working depth	21 m

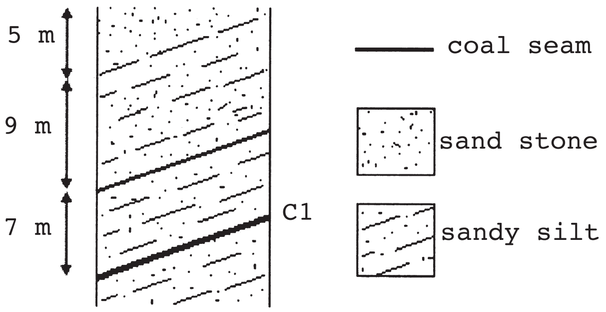

Figure 7—Stratigraphic column over panel area in Negin coalmine

The maximum surface subsidence measured was 0.798 m. Table II shows the measured parameters according to the surface subsidence data collected from a field survey.

An empirical relationship has been obtained between the parameters defining the profile function and geological and mining conditions (Table III).

Using the above specific parameters of the site in the new model, the following function has been set-up for Negin coalmine:

$$S(x) = -0.798x\left[c \cdot e^{-8.8\left(\frac{-x}{70}\right)^{2.17}} + d \cdot e^{-7.4\left(\frac{x}{133}\right)^{2.11}}\right] \quad [12]$$

The monitored subsidence and results of the calculation using the above function are presented in Table IV.

In this table, x is the horizontal distance from the maximum subsidence location.

The results of the calculation with the new function indicate that the predicted value was in good agreement with the measured data (Figure 9).

Correlation between predicted values and observed value is 0.999; it is a good agreement for two data sets.

Table II

Measured parameters for profile function in Negin coalmine

Parameter	Value
βu	47.7°
βl	55°
θ	7°

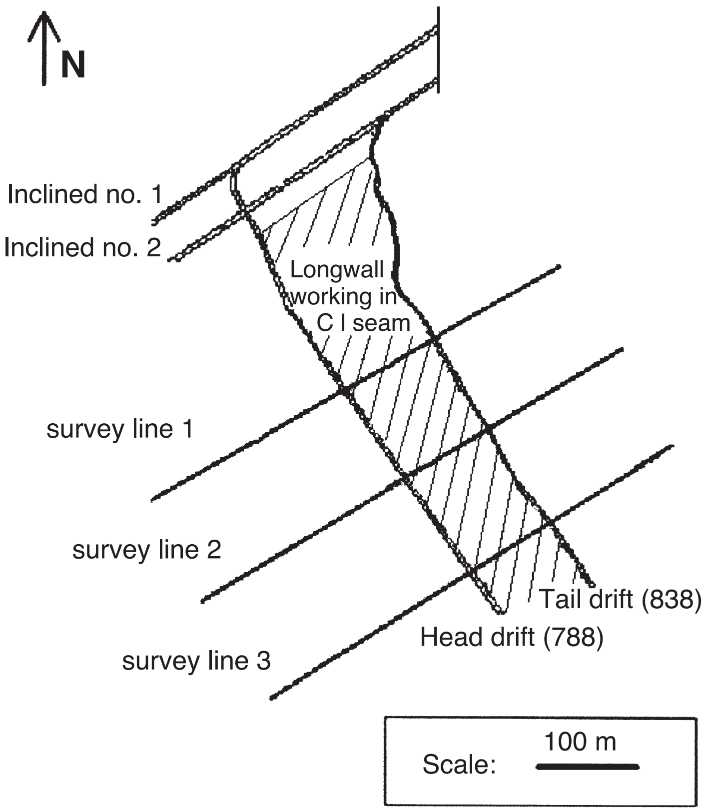

Figure 8—Negin coalmine plan in seam C1 and survey lines

Conclusions

In this study, a new profile function is proposed. It is formed from the sum of two negative exponential functions that have been adjusted to three survey lines in a case study in the Negin coalmine east of Iran.

Because of the simplicity of the profile function, the use of the new model decreases the calculation time for predicting surface subsidence and enhances the precision of subsidence prediction.

The results gained from surface subsidence measurements at Negin coalmine show an excellent correlation between the measured and the predicted subsidence by using the new model. The correlation coefficient was 0.999, which is very high.

Table III

Profile function parameters in Negin coalmine

Parameter	Value
f	8.80
g	2.17
p	7.40
q	2.11

Table IV

Monitored and predicted subsidence in Negin coalmine

X (m)	Predict (m)	Observed (m)
-70	0	0
-60	-0.001	-0.015
-50	-0.011	-0.011
-40	-0.058	-0.045
-30	-0.196	-0.220
-20	-0.446	-0.446
-10	-0.701	-0.705
0	-0.798	-0.798
10	-0.773	-0.763
20	-0.696	-0.674
30	-0.579	-0.579
40	-0.443	-0.460
50	-0.311	-0.311
60	-0.200	-0.195
70	-0.117	-0.117
80	-0.063	-0.081
90	-0.031	-0.031
100	-0.014	-0.008
110	-0.005	-0.005
120	-0.002	-0.025
130	-0.001	-0.001
140	0	0

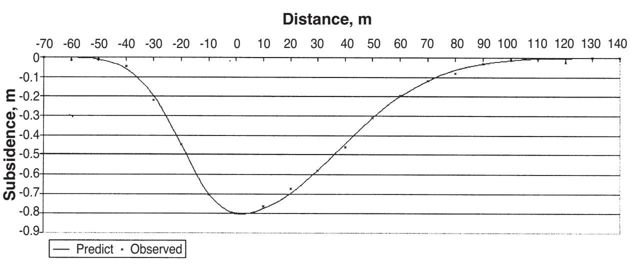

Figure 9—Observed and predicted subsidence in Negin coalmine

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