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A NEW PREDICTION MODEL OF SURFACE SUBSIDENCE WITH CAUCHY DISTRIBUTION IN THE COAL MINE OF THICK TOPSOIL CONDITION

Coal is the main energy source in China, but its underground mining causes surface subsidence, which seriously damages the ecological and living environments. How to calculate subsidence accurately is a core issue in evaluating mining damage. At present, the most commonly used method of calculation is the Probability Integral Method (PIM), based on a normal distribution. However, this method has limitations in thick topsoil (thickness > 100 m), in that the extent of the calculated boundary of the subsidence basin is smaller than its real extent, and this has an undoubted impact on the accurate assessment of the extent of mining damage. Therefore, this paper introduces a calculation model for surface subsidence based on a Cauchy distribution for thick topsoil conditions. This not only improves the accuracy of calculation at the subsidence basin boundary, but also provides a universal method for the calculation of surface subsidence.

Keywords: Coal mining; Thick topsoil; Surface subsidence; Probability Integral Method; Cauchy distribution; Calculation model

1. Introduction

Coal is the main energy source in China (Wang et al., 2019; Xin et al., 2019), but its underground mining causes surface subsidence, which seriously damages the ecological and living environments (Tiwary, 2001; Polanin et al., 2019) and also affects the sustainability of mining operations. Due to the vast territory of China and the complex geological conditions of coal seams, the question of how to calculate surface subsidence accurately is a core issue in evaluating

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mining damage. Attempts to calculate surface subsidence go back more than one hundred years (Goldreich, 1913; Whittaker & Reddish, 1989). The modern method of calculation was originated in 1951 by the Polish mining engineer Stanisław Knothe (Knothe, 1957), who took the normal distribution as the mining influence function based on actual observations, and then established a calculation model for surface subsidence (Tajduś, 2009). In 1954, another Polish engineer, Jerzy Litwiniszyn, considered surface subsidence by mining as a random process (Litwiniszyn, 1954, 1974), and then used a random walk model to determine the mining influence function as a normal distribution. This method has been widely used in Europe, the United States, Canada, South Africa, Australia and China, which are the most developed mining countries (Peng, 2015; Gruszczyński et al., 2018; Hegemann, 2018; Jiang et al., 2018; Misa et al., 2018; Preusse et al., 2018; Tajduś et al., 2018). Meanwhile, it extends to many models in different areas, for instance, rock salt (Jing et al., 2018; Sroka et al., 2018), petroleum and natural gas (Sroka & Tajduś, 2009; Fernando Paullo Muñoz et al., 2017, Sroka et al., 2018a, 2018b), groundwater (Sroka, 2005) and tunnel excavation (Liu & Zhang, 1995; Liu et al., 2018).

The model of calculation of surface subsidence based on a normal distribution is known in China as the Probability Integral Method (PIM) (Liu & Liao, 1965; Liu & Dai, 2016). After several years of research, it has been determined that the surface subsidence in conditions of thick topsoil (thickness > 100 m) is significantly different from that found in normal conditions (no topsoil or topsoil thickness < 20 m). Therefore, this model has some limitations, namely that the calculation is inaccurate in case of thick topsoil.

The strata of some coal mines in eastern China are atypical; in particular, the topsoil thickness is approximately 200-600 m. In these conditions, the surface subsidence basin is larger than in normal conditions, and the PIM calculation boundary is smaller than the actual boundary (Wang et al., 2012a, 2012b; Chen et al., 2013). This means that the determination of the boundary of mining subsidence is inaccurate, which seriously affects the accurate assessment of land subsidence, building damage and environmental damage. Therefore, the PIM parameters are sometimes revised in conditions of thick topsoil (Guo et al., 2016; Ren, 2018), but this revised method adds extra parameters, which are also assumed to depend on the specific geological conditions. Other researchers consider the relationship between surface subsidence and topsoil deformation (Sui & Di, 1999), but this method is complex in practice.

Therefore, this paper introduces a model for the calculation of surface subsidence in conditions of thick topsoil, based on the Cauchy distribution. It not only improves the accuracy of calculation at the boundary of the subsidence basin, but also provides a universal and convenient method for the calculation of surface subsidence.

2. Method of calculation of surface subsidence

Mining spaces (goafs) will be formed in the coal seam after mining. Because the spaces are not able to support the weight of the overburden, the overburden falls from the top of the spaces. This process will slowly spread to the surface, and finally a subsidence basin will be formed on the surface (Fig. 1).

At present, assuming that the mining influence function follows a normal distribution, the calculation model for surface subsidence is established using probability theory. For instance, when the plane of the working face and the major cross-section are subject to the conditions of long-wall mining, the coordinate y ranges from negative infinity to positive infinity ($y \in (-\infty, +\infty)$)

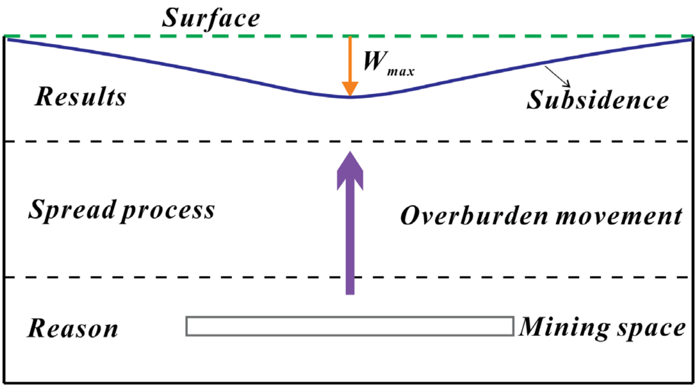

Fig. 1. The reason and process of surface subsidence

and x from zero to positive infinity ($x \in [0,+\infty)$). This mining method is known as semi-infinite extraction (Fig. 2).

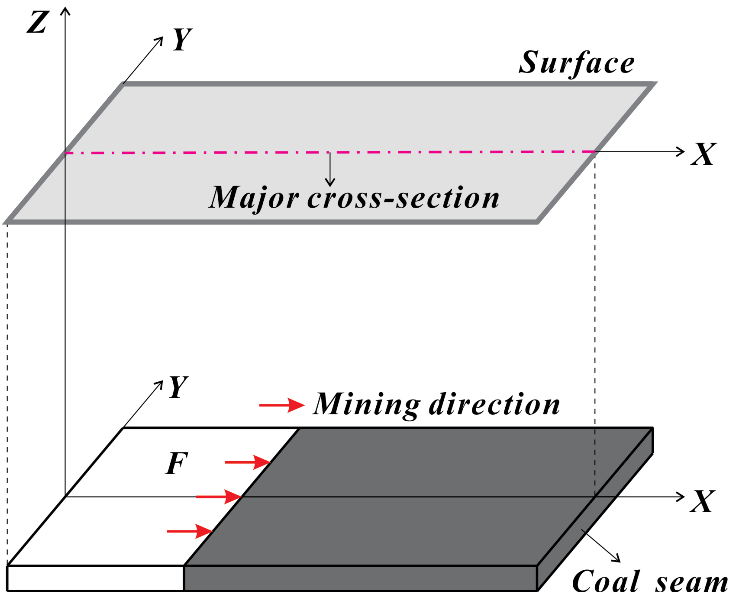

Fig. 2. The working face and major cross-section

The surface subsidence of the major cross-section in semi-infinite extraction is given by

$$W(x) = W_{\max} \int_F f(x)dx \tag{1}$$

where $W_{\max}$ is the maximum subsidence, $f(x)$ is the mining influence function, F is the mining area.

The most commonly used function is the Knothe function, which is a normal distribution with $\mu = 0$ (mean) and $\sigma = \frac{r}{\sqrt{2\pi}}$ (variance). The Knothe function (Tajduś, 2009) can be expressed in the $XO_A Z$ coordinate system (Fig. 3) as

$$f(x) = \frac{1}{r} e^{-\pi \frac{x^2}{r^2}}, \quad r = \frac{H}{\tan \beta} \tag{2}$$

where r is the major influence radius, H is the mining depth, tanβ is the tangent of the main influence angle.

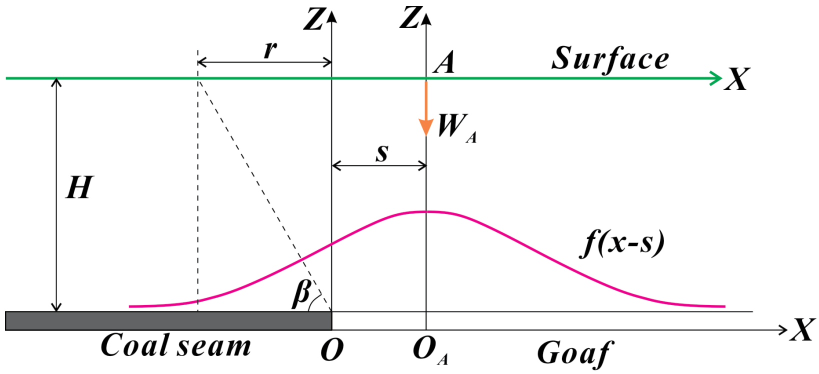

Fig. 3. Calculation coordinate system for semi-infinite extraction

The coordinate origin (O_A) is translated to a new position (O) where mining of the coal seam begins. The horizontal distance from O_A to O is S, so the new coordinate system (XOZ) replaces the original one. In the original coordinate system ($XO_A Z$), the mining influence function is $f(x)$, hence the function is $f(x - s)$ in the new coordinate system (XOZ). Therefore, the subsidence of point A on the surface is given by equation (3), on condition that x lies in the range zero to positive infinity in the XOZ system.

$$\begin{aligned} W_A &= W_{\max} \int_0^{\infty} f(x-s)dx = W_{\max} \int_{-s}^{\infty} f(x)dx \\ &= \frac{W_{\max}}{\sqrt{\pi}} \int_{-\sqrt{\pi}\frac{s}{r}}^{\infty} e^{-\lambda^2} d\lambda \end{aligned} \tag{3}$$

According to equation (3), the subsidence of point A is the following:

$$W_A = \frac{W_{\max}}{\sqrt{\pi}} \int_{-\sqrt{\pi}\frac{s}{r}}^{\infty} e^{-\lambda^2} d\lambda = \frac{W_{\max}}{\sqrt{\pi}} \left[\int_{-\sqrt{\pi}\frac{s}{r}}^{0} e^{-\lambda^2} d\lambda + \int_0^{\infty} e^{-\lambda^2} d\lambda \right] = \frac{W_{\max}}{2} \left[erf\left(\frac{\sqrt{\pi}}{r} s \right) + 1 \right] \tag{4}$$

where $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$, $\int_0^{\infty} e^{-\lambda^2} d\lambda = \frac{\sqrt{\pi}}{2}$.

The horizontal coordinate of point *A* is equal to *S* in the *XOZ* system. Therefore, the subsidence function of any point in semi-infinite extraction is given by equation (5):

$$W(x) = \frac{W_{\max}}{2}\left[erf(\sqrt{\pi}\frac{x}{r}) + 1 \right] \tag{5}$$

This method of calculation based on the Knothe function is known in China as the Probability Integral Method (PIM), and it is extensively applied in calculating surface subsidence (Li et al. 2016, 2018). However, it is not suitable for thick topsoil, and therefore a new function is needed to overcome this weakness of PIM.

3. Cauchy distribution

The Cauchy distribution is a continuous probability distribution with the following probability density function (Fang et al., 2016; Gu et al., 2017).

$$f_C(x, x_0, \gamma) = \frac{1}{\pi\gamma\left[1 + \left(\frac{x - x_0}{\gamma}\right)^2\right]} = \frac{1}{\pi}\left[\frac{\gamma}{(x - x_0)^2 + \gamma^2}\right] \tag{6}$$

where x_0 is a position parameter, γ is a scale parameter.

In the standard Cauchy distribution, x_0 is equal to zero and γ is equal to one, and the probability density function is given by equation (7):

$$C(0,1) = \frac{1}{\pi(1 + x^2)} \tag{7}$$

The curve shapes of the Cauchy and normal distribution density functions are similar (Fig. 4), but the tail of the Cauchy distribution is longer than that of the normal distribution. It thus provides another function model to describe the subsidence boundary.

4. Calculation model and parameters of semi-infinite extraction with Cauchy distribution

4.1. Subsidence model for semi-infinite extraction

Assuming the mining influence function is a Cauchy distribution density function ($x_0 = 0$), the function is the following:

$$f_C(x) = \frac{1}{\pi}\left[\frac{\gamma}{x^2 + \gamma^2}\right] \tag{8}$$

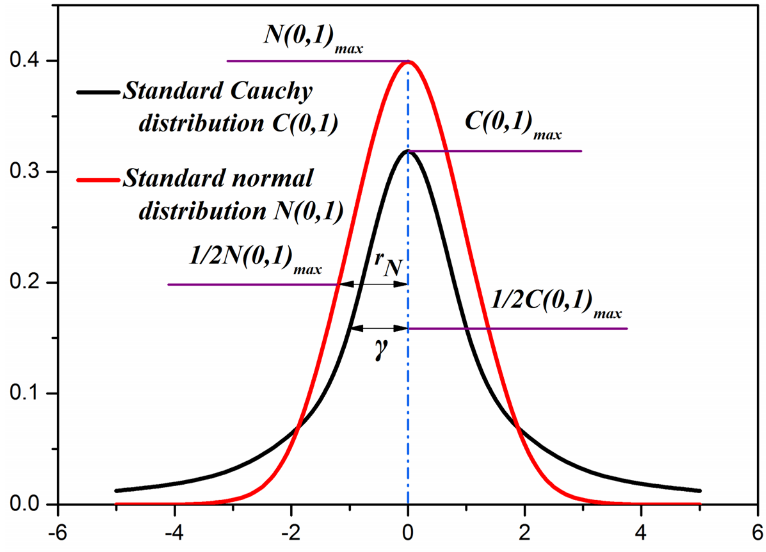

Fig. 4. Distribution density curves of standard Cauchy and normal distributions

In the *XOZ* coordinate system (Fig. 3), the subsidence of point *A* in semi-infinite extraction, given by equation (3), is equal to:

$$W_A = W_{\max}\int_{-s}^{\infty} f_C(x)dx = W_{\max}\int_{0}^{\infty} f_C(x-s)dx$$
$$= W_{\max}\int_{0}^{\infty}\frac{1}{\pi}\cdot\frac{\gamma}{(x-s)^2+\gamma^2}dx = W_{\max}\left(\frac{1}{2}+\frac{1}{\pi}\arctan\frac{s}{\gamma}\right) \quad (9)$$

Therefore, the subsidence of any point on the surface in semi-infinite extraction is given by equation (10):

$$W(x) = W_{\max}\left(\frac{1}{2}+\frac{1}{\pi}\arctan\frac{x}{\gamma}\right) \quad (10)$$

(1) As $x \to -\infty$, the surface subsidence approaches the maximum; (2) when $x = 0$, the subsidence is equal to a half of the maximum, namely that above the location of the start of mining; (3) as $x \to \infty$, the subsidence approaches zero, so the subsidence away from the mining area is zero.

The subsidence curve given by equation (10) is similar to the actual subsidence curve. Therefore, it may be appropriate to use a Cauchy distribution as the mining influence function.

4.2. Parameters of the Cauchy distribution

The scale parameter (γ) is the half-width at half-maximum of the Cauchy density function. Hence, according to equation (8), with x equal to $\pm\gamma$, $f_C(x=\pm\gamma) = \frac{1}{2} f_C(x)_{\max}$.

Because of the similarity between the Cauchy and normal distributions, assuming the "equivalent scale parameter" of the normal distribution is r_N (Fig. 4), the probability density function of the normal distribution is given by equation (11):

$$f_N(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{11}$$

When μ and x are both equal to zero, the maximum of $f_N(x)$ should be the following:

$$f_N(x)_{\max} = \frac{1}{\sqrt{2\pi}\sigma} \tag{12}$$

Therefore, the equivalent scale parameter (r_N) is given by:

$$\begin{cases} f_N(x = \pm r_N) = \frac{1}{2} f_N(x)_{\max} \\ \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{r_N{}^2}{2\sigma^2}\right) = \frac{1}{2} f_N(x)_{\max} = \frac{1}{2} \times \frac{1}{\sqrt{2\pi}\sigma} \\ r_N = 1.18\sigma \end{cases} \tag{13}$$

According to the similarity between the Cauchy and normal distributions, the scale parameter (γ) is equal to the equivalent scale parameter (r_N).

The scale parameter can be calculated using the results for σ. However, σ is the variance of the normal distribution, hence the results for σ should be calculated with the normal distribution.

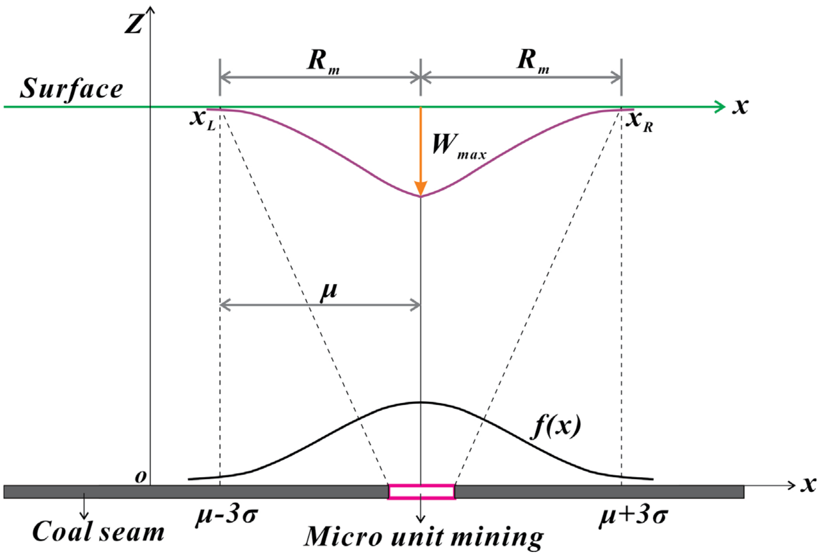

Fig. 5. Relationship between the mining influence function and surface subsidence

The influence of micro unit mining follows a normal distribution in the Cartesian coordinate system (Fig. 5).

According to the Pauta criterion (3σ criterion), the probability of $x - \mu$ lying between -3σ and 3σ is 99.74%; in other words, the probability of subsidence outside the boundary points x_L and x_R is 0.26%. This implies that the subsidence at the boundary points x_L and x_R is zero, namely that these two points are the boundaries of the surface subsidence basin.

Assuming that the mining width (dx) of a micro unit approaches zero, the length of the subsidence basin ($2R_m$) is given by equation (14):

$$\begin{cases} 2R_m = x_R - x_L = 6\sigma \\ R_m = 3\sigma \end{cases} \tag{14}$$

In the actual situation, half the length of the subsidence basin is the mining influence radius (R_m), which is the horizontal distance from the mining boundary to zero surface subsidence. Values of R_m can be directly measured. Therefore, the relationship between R_m and γ and the major influence radius (r) is expressed as follows:

$$\begin{cases} \gamma = 1.18\sigma \\ \sigma = \dfrac{r}{\sqrt{2\pi}} = \dfrac{r}{2.5} \\ \sigma = \dfrac{1}{3} R_m \\ \gamma = 0.4R_m = 0.48r \end{cases} \tag{15}$$

In summary, the calculation model for semi-infinite extraction based on the Cauchy distribution is expressed by equation (16):

$$W(x) = W_{\max}\left[\frac{1}{2} + \frac{1}{\pi}\arctan\left(2.08 \cdot \frac{x}{r}\right)\right] \tag{16}$$

5. Examples

5.1. Geological conditions

The geological conditions and parameters of working face 1301N are shown in Table 1. Mining at 1301N began in September 2009 and ended in April 2011, and subsidence measure-

TABLE 1

Geological conditions and parameters

Length (m)	Width (m)	Topsoil thickness (m)	Overburden thickness (m)	Dip angle (deg.)	Coal seam thickness (m)	Maximum subsidence ($W_{\max}$) (mm)	Tangent of main influence angle ($\tan\beta$)	Major influence radius (r) (m)
2515	220	620	190	5.0	9.0	3467	2.0	405

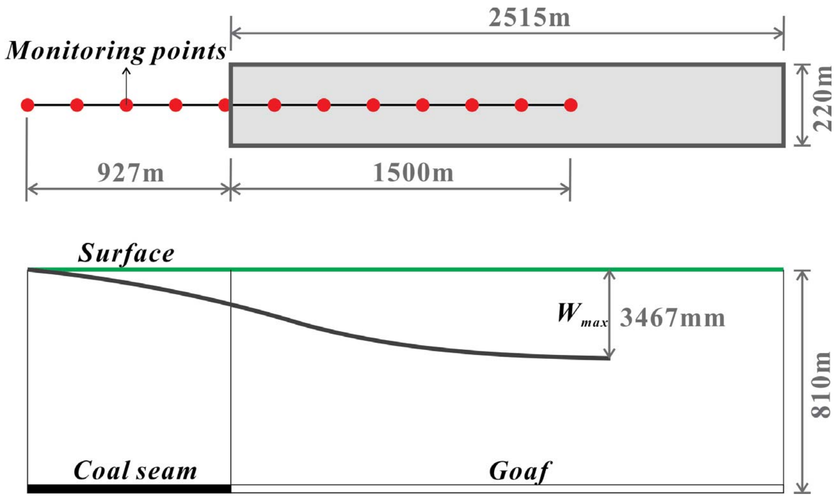

Fig. 6. Plan of observation stations

ments began on 3 August 2009 and ended on 26 October 2011. Observations were made 39 times in the mining period, and the average distance between monitoring points was 60 m (Fig. 6).

5.2. Analysis of results

The accuracy of the Cauchy and PIM models may be evaluated based on standard deviation. For evaluation purposes, the models are divided into two parts (Fig. 7).

(1) For $x/r < 0$ (monitoring points above the coal seam), the Cauchy standard deviation is ±78.90 mm and the PIM standard deviation is ±262.66 mm, hence the accuracy of the Cauchy model is greater than that of the PIM model in this interval.

(2) For $x/r > 0$ (monitoring points above the goaf), the Cauchy standard deviation is ±288.58 mm and the PIM standard deviation is ±105.68 mm, hence the accuracy of the Cauchy model is less than that of the PIM model in this interval.

Because of the different accuracies at different intervals, a combined model is adopted for higher accuracy. The Cauchy model is suitable for use in the region above the coal seam, and PIM in the region above the goaf:

$$W(x)_{com} = \begin{cases} W_{\max}\left[\frac{1}{2} + \frac{1}{\pi}\arctan(2.08\frac{x}{r})\right], \frac{x}{r} \le 0 \\ \frac{W_{\max}}{2}\left[erf(\sqrt{\pi}\frac{x}{r}) + 1\right], \frac{x}{r} > 0 \end{cases} \tag{17}$$

The standard deviation of the combined model is ±94.86 mm, which is smaller than for both the Cauchy model (±244.45 mm) and PIM (±191.19 mm). The combined model also gives the best fit to the observations (Fig. 8).

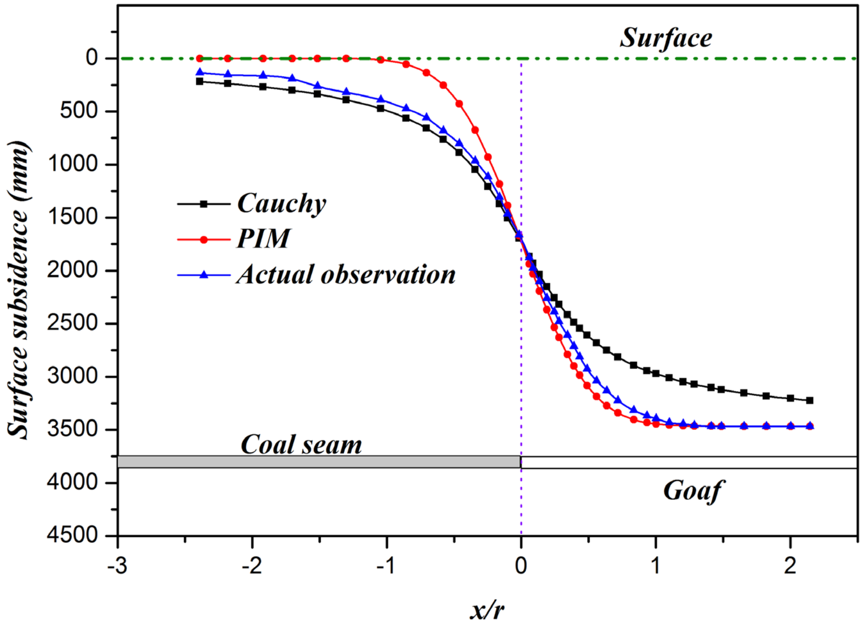

Fig. 7. Subsidence calculated using two models and observations

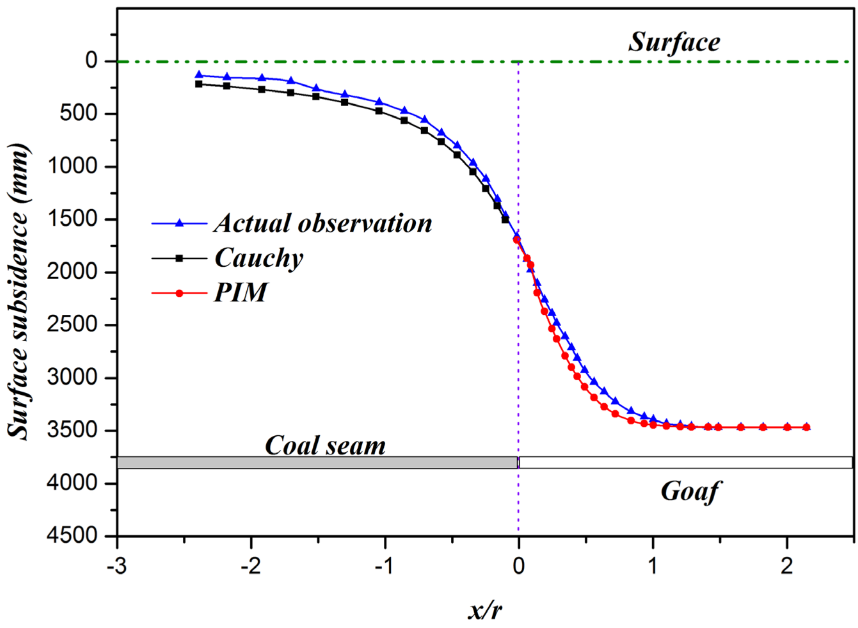

Fig. 8. Subsidence calculated using the combined model and observations

6. Conclusions

(1) In conditions of thick topsoil, the extent of subsidence calculated by PIM is less than the actual extent.
(2) A calculation model for surface subsidence based on the Cauchy distribution was constructed. When the calculation accuracy of the two models was compared based on actual observations, the results indicated that the Cauchy model is suitable for the region above the coal seam, and PIM for the region above the goaf.
(3) The combined model with Cauchy and PIM not only improves the accuracy of calculation at the boundary of the subsidence basin, but also easily provides a universal method for the calculation of surface subsidence, partly similar to the solution provided by Knothe in 2005 (Knothe, 2005).

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