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Research Article

Study on the Law of Subsidence of Overburden Strata above the Longwall Gob

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In recent years, with the increase of depth and intensity of coal mining, geological disasters in deep engineering occur frequently. It is essential to study the law of subsidence of overburden after mining for analyzing the mechanism and control of geological disasters in deep engineering. However, the value of the subsurface subsidence factor and other overburden subsidence parameters could not be obtained easily. In this paper, the strata bulking of the caving zone, the bed separation of the fractured zone, and the dilatation of bending zone were considered a kind of expansion in the vertical direction uniformly. An assumption on vertical expansion value distribution of overburden strata above the longwall gob was proposed. Based on the assumption, a formula of the subsurface subsidence factor was deduced according to such parameters as the bulking factor, mining depth, mining height, and surface subsidence factor. Moreover, many field data were used to verify the correctness of the assumption by the data fitting method. The results show that the exponential function could well describe the expansion distribution characteristic of overburden strata and subsurface subsidence in the vertical direction. The parameter a in the deduced formula influences the shape of the subsurface subsidence curve; it is called the subsurface subsidence influence factor (SSIF). The SSIF, maximal vertical expansion value, and the mining depth-to-mining height (MD/MH) ratio influence the subsurface subsidence factor. The expansion distribution (E-D) factor is defined to describe the subsidence characteristic of overburden strata above the longwall gob by the surface subsidence factor and bulking factor of the caving zone. The E-D factor presents the logarithm relation with the MD/MH ratio, and the range of its maximum is 2.84~3.40. The case study demonstrates that the subsurface subsidence factor calculated by the proposed method has higher precision, and the mean errors between the calculated value and the measured value are less than 2%.

1. Introduction

The longwall working surface of coalmine distributes widely in the world. The overburden strata above the longwall working face are suspended in a large area, which is easy to cause coalmine disaster accidents such as rock bursts and a strong mine pressure. As is known to all, after excavated, the overburden strata above the longwall gob could be divided into such three zones as caving zone, fractured zone, and bending zone [1, 2]. Although the deformation and movement features among the "Three Zones" show the obvious difference, the fact that the surface subsidence value is less than the mining height indicates the expansion generality among them. The subsurface subsidence above the longwall gob has been used in many fields, including feasibility judgment and design for ascending mining [1, 3–6], mining of protective coal seam, depressurized mining for rock bursts and coal and gas outburst mine [1, 3–6], and destruction of coalmine roadway and chamber [7–9], surface waters protection [10, 11], and tunnel excavation above the longwall gob [12, 13]. Hence, the study on the subsurface subsidence can provide a vital fundamental basis for engineering works above the longwall gob.

Based on the motion features of overburden strata above the longwall gob, plenty of studies on the subsurface subsidence have been developed from such angles as surface subsidence and overburden strata structure, respectively. Many scholars have studied the relation between surface subsidence factor and subsurface subsidence factor according to the surface subsidence theory. Considering the hard rock proportion and overburden stratification, Luo et al. [10, 11] obtained the enhanced subsurface subsidence prediction model on the basis of the influence function method. The results of physical simulation tests [14] showed the quadratic relation between the surface subsidence factor and subsurface subsidence factor above the longwall gob:

$$q_z = q_0\left(a_1(z/H)^2 + a_2(z/H) + a_3\right), \tag{1}$$

where q_z and q_0 are the subsurface subsidence factor and surface subsidence factor, respectively, z and H are the depth away from the surface and the mining depth, the ratio of strata depth to mining depth (z/H) is called the depth level, and a_1, a_2, and a_3 refer to the parameters relevant to mining and geological conditions.

Based on Fangezhuang Coalmine's field data, Li [15] obtained the function relation between surface subsidence factor and subsurface subsidence factor as follows:

$$q_z = 1 - (1 - z/H)^n(1 - q_0), \tag{2}$$

where n refers to the parameters relevant to mining and geological conditions.

The above studies show the relation between surface subsidence and subsurface subsidence above the longwall gob to some extent. However, the influences of such geological and mining factors as mining depth, mining height, and strata collapse condition were not shown.

From the angle of overburden strata structure, the thick and hard strata in the fractured zone not only have major control significance for surrounding rock on the longwall working face but also play the control action on subsurface and surface subsidence [16, 17]. Qian and Miao [18] obtained voussoir beam's subsidence curve through a study on the voussoir beam theory. Xu and Qian [19] obtained the relation formula between the length of voussoir beam and the key strata subsidence with different breaking spans of the main roof by the UDEC software. This relation formula has better accuracy under the condition of a hard roof and lesser unconsolidated layers. Wu et al. and Zhou et al. [20, 21] monitored the vertical movements in internal rock with the borehole extensometer system and studied the density distribution of mining-induced fracture interspace above the longwall gob.

Many studies [22–25] show that the expansion decreases along with the increase of distance away from the gob. In the classical "Three Zones" theory, the bulking factors of "Three Zones" are 1.25-1.4, 1.05-1.15, and 1.01-1.02 successively from bottom to top [22]. Peng [26] and Deng et al. [27] discovered that the bulking factor decreases along with mining depth in certain disciplines in the vertical direction based on the method of statistics and physical simulation, respectively. Wang et al. [28] assumed that the vertical expansion value shows the linear change in the vertical direction to obtain the relation between the vertical expansion value and the ratio of bedrock thickness and mining height. Yavuz [29] proposed a method that the stress recovery distance in the gob and deems that the "Three Zones" have different strains, the caving zone's strain should follow Salamon's equation, the fractured zone's strain is about 0.4%, and the strain of bending zone does not change. Through this method, the surface subsidence value can be calculated, but not the subsurface subsidence.

Various methods have been adopted to investigate the relationship between subsurface subsidence factor and surface subsidence factor or overburden strata structure or bulking factor. Each parameter in the above studies is determined by a variety of factors, and the subsurface subsidence factor cannot be calculated accurately by any one of these parameters. And more, the mining and geological conditions' effects for subsurface subsidence have not been fully revealed. Thence, such parameters as mining depth, mining height, bulking factor, and surface subsidence factor should be considered to describe the subsurface subsidence above the longwall gob.

A method for determining subsurface subsidence based on overburden strata expansion above the longwall gob was proposed in this paper. In this method, the vertical expansion value in the overburden strata above the longwall gob is assumed to obey an exponential distribution in the vertical direction, and the relation between it and surface subsidence factor, mining depth, and mining height was deduced. On the base of the collection of a large number of field data, the correctness of this method was verified through parameter fitting and comparison with field data, and parameters of the distribution function of the subsurface subsidence factor were determined. Then the distribution discipline of the subsurface subsidence factor above the longwall gob was obtained. Finally, parameters of the distribution function of the subsurface subsidence factor were discussed and a case was analyzed.

2. Methods

2.1. Assumption. As shown in Figure 1, the bulking of the caving zone, the strata structure action of the fractured zone, and the bed separation and dilatation of the bending zone are uniformly considered a kind of expansion in the vertical direction. Moreover, the basic assumption is as follows.

(1) The vertical expansion value of strata could be described by the continuous function

(2) The study is based on the critical and supercritical longwall gob

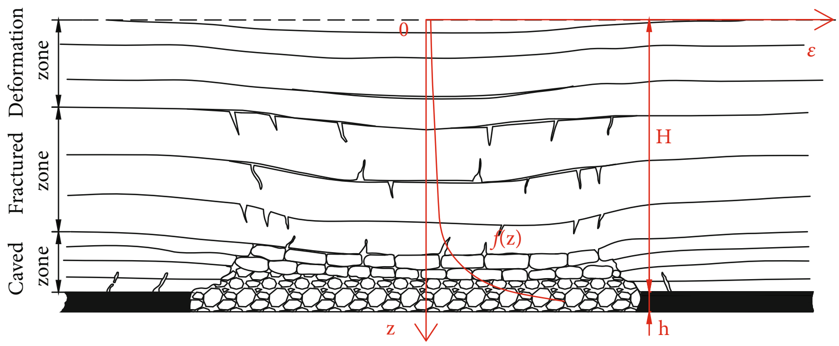

Figure 1: Distribution of "Three Zones" [26] and expansion distribution above the longwall gob.

(3) The coal seam is a nearly flat seam and gently inclined seam and the dip of a coal seam is assumed as $\alpha°$ (less than 25°)

(4) The vertical displacement of the floor in the gob is neglected

2.2. Model Establishment. Establish the rectangular plane coordinate system as shown in Figure 1. The vertical axis and horizontal axis refer to the depth from the ground and vertical expansion value of overburden strata, respectively. In Figure 1, $f(z)$ is the distribution function of vertical expansion value, and H and h are mining depth and mining height, respectively.

Based on relevant studies and numerous field experiences [22–24, 26–28], the vertical expansion value for overburden strata above the longwall gob is fiercer on change than the description by linearity and quadratic function. Thence, when a single coal seam is extracted, it is assumed that the change of vertical expansion value follows the exponential function:

$$f(z) = \lambda a^{(z-H)/h}, \quad (3)$$

where $f(z)$ is the distribution function of the vertical expansion value, z is depth, the parameters of λ and a are undetermined parameters, H is mining depth, and h is mining height.

The strata of caving zone are provided with maximal vertical expansion value, and according to the formula of maximum compression strain of bulked rock material [29], the maximal vertical expansion value could be expressed by the bulking factor of a caving zone:

$$\varepsilon_0 = \Delta l/l = (b_0 - 1)/1, \quad (4)$$

where ε_0 is the maximal vertical expansion value and b_0 is the bulking factor of a caving zone.

The equation of the vertical expansion value in the vertical direction is

$$\varepsilon(z) = \varepsilon_0 f(z) = \varepsilon_0 \lambda a^{(z-H)/h}. \quad (5)$$

The sum of surface subsidence value and accumulative vertical expansion value of overburden strata is equal to mining height. Therefore, the subsurface subsidence value W_z could be calculated by the following formula:

$$W_z = h - \int_H^z \varepsilon_0 f(z)dz = h - \frac{\lambda h \varepsilon_0}{\ln a}\left(a^{(z-H)/h} - 1\right). \quad (6)$$

Based on the relation between subsidence value and subsidence factor [30], the subsurface subsidence factor q_z is

$$q_z = 1 - \frac{\lambda \varepsilon_0}{\ln a}\left(a^{(z-H)/h} - 1\right). \quad (7)$$

When $z=0$, the surface subsidence factor q_0 is

$$q_0 = 1 - \frac{\lambda \varepsilon_0}{\ln a}\left(a^{-(H/h)} - 1\right). \quad (8)$$

Through formulas (7) and (8), the relation between surface subsidence factor and subsurface subsidence factor could be obtained as follows:

$$q_z = 1 - (1 - q_0)\left(a^{(z/H-1)(H/h)} - 1\right) / \left(a^{-(H/h)} - 1\right). \quad (9)$$

3. Parameter Determination and Correctness Verification

3.1. Parameter Determination. Firstly, collect the data involved in the formula, including the surface subsidence factor, bulking factor of a caving zone, mining depth, and mining height. The working face in which the length of the panel is greater than 1.4 times of mining depth was selected and was considered a critical or supercritical working face [29]. Secondly, the transposition and arrangement were conducted for formula (8), and then the logarithm on both sides was taken to obtain the following form:

$$H/h = A \ln (1 + BT), \quad (10)$$

where $(1 - q_0)/\mathcal{E}_0 = T$ is defined as the expansion distribution factor (E-D factor), $A = -1/\ln a$, and $B = \ln a/\lambda$.

Finally, based on the collected data and formula (10), implement the regression fitting to obtain the value of λ and a and then determine the variation tendency of vertical expansion as well as the subsurface subsidence factor (q_z).

Table 1: Relevant parameters list of coalmines.

Mine	ε_0	q_0	h (m)	H (m)	$(1-q_0)/\varepsilon_0$	H/h
Qinghemen Mine	0.2	0.66	1.8	224	1.70	124.44
Taiji No.1 Mine	0.35	0.65	1.6	120	1.00	75.00
Baoan No.1 Mine	0.38	0.83	2.1	122	0.45	58.10
Fengfeng 0252	0.42	0.84	2.4	133	0.38	55.42
Zaozhuang 2042	0.58	0.76	1.45	61	0.41	42.07
Panxi Mine	0.58	0.68	2.2	91	0.55	41.36
Macun Mine	0.38	0.83	2.2	128	0.45	58.18
Pingdingshan No.10 Mine	0.39	0.80	2.0	115	0.51	57.50
Pingdingshan No.6 Mine	0.22	0.83	3.0	281	0.77	93.67
Dongzhuang Mine (107)	0.30	0.83	2.0	156	0.57	78.00
Quantai Mine	0.34	0.78	2.1	146.5	0.65	69.76
Hongshandian Mine	0.41	0.63	2.0	114.6	0.90	57.30
Gengcun Mine	0.53	0.60	3.0	146	0.75	48.67
Gengcun Mine	0.22	0.66	2.4	280	1.55	116.67
Wangjiayuan Longjiachong	0.21	0.62	1.5	195	1.81	130.00
Gaokeng Mine	0.19	0.63	1.05	170	1.95	161.90
Dongliang No.2 Mine	0.51	0.91	1.67	67	0.18	40.12
Wuyang Mine	0.39	0.72	3.0	213	0.72	71.00
Nantun Mine	0.17	0.78	2.9	284	1.29	97.93
Qinghemen No. 2 Mine	0.15	0.67	1.6	318.5	2.20	199.06
Fengfeng 0227	0.20	0.72	4.9	459	1.40	93.67
Dongzhuang Mine (113)	0.28	0.85	2.1	159.5	0.54	75.95
Baodian Mine	0.23	0.83	5.8	427	0.74	73.62
Xie'er Mine	0.41	0.77	6.6	288	0.56	43.64
Shizui Mine	0.31	0.86	4.7	268	0.45	57.02
Beisu Mine	0.08	0.80	0.92	305	2.50	331.52

3.2. Data and Processing. Many field data for coalmines' surface subsidence and basic parameters were collected in the reference [30]. Moreover, twenty-six coalmines with the critical and supercritical longwall gob were selected, whose detailed data are shown in Table 1. In the table, the maximal vertical expansion value $\mathcal{E}_0$ is calculated by formula (4), the E-D factor and MD/MH ratio are calculated by the form of $(1-q_0)/\mathcal{E}_0$ and H/h.

3.3. Correctness Verification. The data in Table 1 is used to verify the correctness of the assumption on vertical expansion distribution. According to formula (10) and the MD/MH ratio and the E-D factor in Table 1, the values of A and B were obtained by data fitting. The fitting result is as shown in Figure 2. In the figure, the x-coordinate is the E-D factor, and the y-coordinate is MD/MH ratio.

The calculated results are as follows: under the 95% confidence interval, $a = 1.0054$ (1.0046, 1.0066) and $\lambda = -0.01681$ (-0.02270, -0.01299). Therefore, the assumption that the vertical expansion value follows an exponential function along with depth change is available.

In order to evaluate the accuracy and adaptability of the method, surface subsidence factors of coalmines in Table 1 were calculated by the proposed method and Yavuz's method [29]. Moreover, the calculated value and field data were compared in Figure 3, in which the horizontal axis and vertical axis are the coalmines number and surface subsidence factor, respectively.

After eliminating a coarse error, the maximum relative error between the calculated two methods and measured values of surface subsidence factors are 20.1% and 18.8%. The average errors of the proposed method and Yavuz's 4method are 2.3% and 6.6%, and the standard deviation of the two methods are 9.9% and 9.1%. The complexity of geological and mining conditions leads to an approximate 20% maximum relative error with both methods. However, both methods have smaller average error and standard deviation. Thus, the correctness and accuracy of the proposed method are further verified by the comparison of surface subsidence.

4. Discussion

4.1. Influences on Subsurface Subsidence

4.1.1. Subsurface Subsidence Influence Factor. Considering that the parameter a influences the shape of the subsurface subsidence factor curve, it is called the subsurface subsidence influence factor (SSIF). Figure 4 shows the distribution

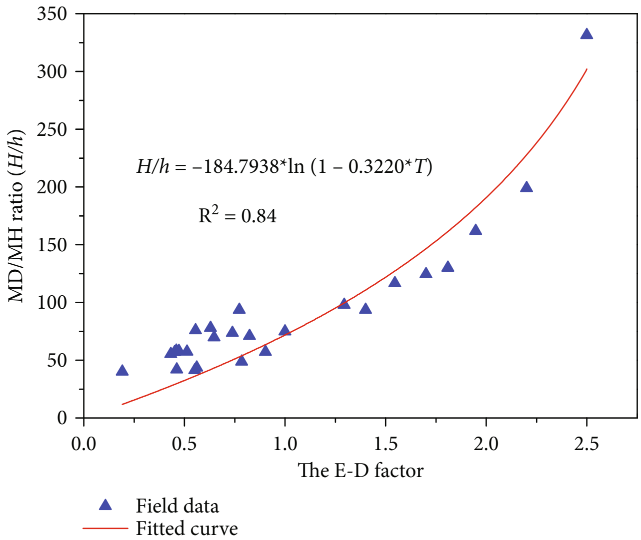

Figure 2: Relation curve between the E-D factor and MD/MH ratio.

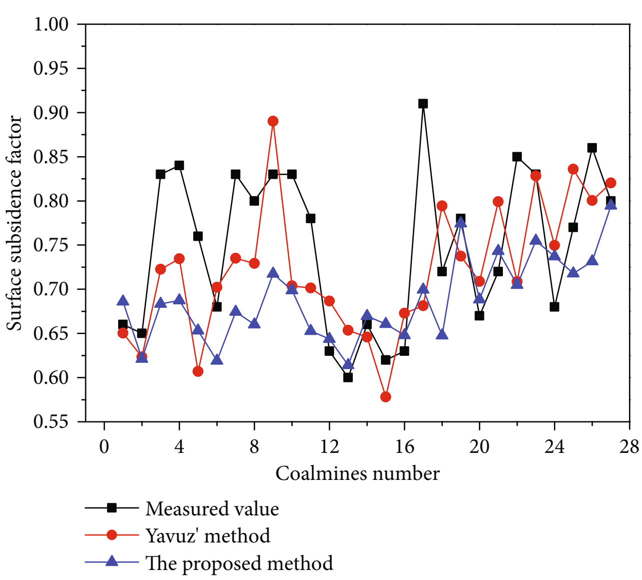

Figure 3: Comparison of the calculated and measured value of surface subsidence factor.

curves of the subsurface subsidence factor with different SSIF. The curves in Figure 4 were drawn based on formula (9). And the parameters with a mean 2.5 m mining height, 0.31 maximal expansion value, and maximal 460 m mining depth were selected from Table 1. The scattered points show the relationship between subsurface subsidence factor and depth level (z/H) after the normalization processing is conducted for surface subsidence factor and mining depth of mines in Table 1. In Figure 4, the vertical axis is the different depth levels (z/H), the horizontal axis is the subsidence factor, and the legend shows the fitted curves of the subsurface subsidence factor with different SSIF.

It could be known from the distribution scope of scattered points in Figure 4 that the value of SSIF should be

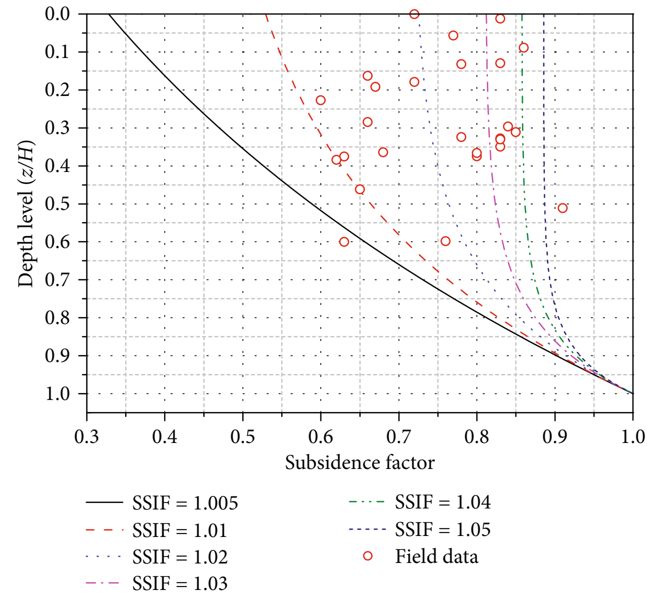

Figure 4: Curves of the subsurface subsidence factor with different SSIF.

greater than 1.0054. Since underground mining has a greater MD/MH ratio, and the MD/MH ratio in Table 1 exceeds 40, therefore, the SSIF of 1.0054 only embodies the change discipline of the subsurface subsidence factor on the section where the MD/MH ratio exceeds 40. On the section less than 40 times mining height, the change of the subsurface subsidence factor is greater and embodies a curve with greater curvature. Therefore, the SSIF should be greater, and the actual subsurface subsidence curve should have greater curvature on the section less than 40 times mining height.

As shown in Figure 4, the SSIF influences the distribution of the subsurface subsidence factor. The bending degree of the distribution curve for the subsidence factor increases along with the increase of the SSIF. The subsurface subsidence factor increases with the SSIF increase; however, the amplification decreases. When the SSIF is equal to 1.0054, the subsurface subsidence factor is small, and the decreasing velocity for the subsidence factor from the roof to the surface is great and uniform, which means that there is an expansion approaching the linearity [28]. When the SSIF increases, the surface and subsurface subsidence factors increase, the change rate of subsidence factor is small, and the expansion focuses on the roof area close to the coal seam (caving zone and fractured zone).

4.1.2. Maximal Vertical Expansion Value. When the values of SSIF are 1.015 and 1.05, respectively, Figure 5 shows the relation between maximal vertical expansion value and subsurface subsidence factor under different depth levels. In Figure 5, a mining depth of 400 m and a mining height of 2 m were adopted, and the horizontal axis and vertical axis are the maximal vertical expansion value and subsidence factor, respectively.

Along with the increase of maximal expansion value, the subsurface subsidence factor for each depth level linearly

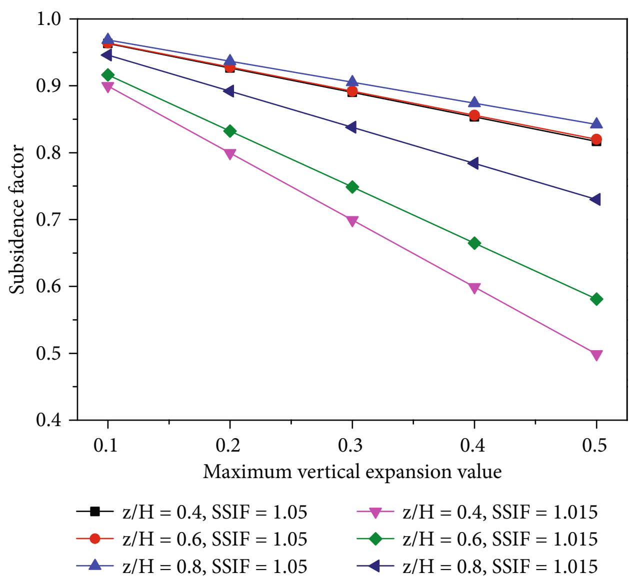

Figure 5: Relation between the subsurface subsidence factor and maximal vertical expansion value.

decreases. The decreased velocity of the subsurface subsidence factor with different depths is different, and it is much less on the depth level close to the coal seam. This shows that the influence degree of the maximal vertical expansion value for subsurface subsidence factor is far greater on the depth level approaching the gob than the surface. When the maximal expansion is identical, along with the depth increase, the difference value of the subsurface subsidence factor with equal depth intervals enlarges. This shows that the subsidence factor variation focuses on the deep section close to the gob. Meanwhile, the greater vertical expansion value means the fiercer subsidence factor variation for strata close to the gob. In addition, when the SSIF is different, the influence of expansion variation on the subsurface subsidence factor is weaker with the increase of the SSIF.

4.1.3. Mining Depth-to-Mining Height (MD/MH) Ratio. When the surface subsidence factor is definitive, different MD/MH ratios influence the subsurface subsidence factor with different depth levels. Figure 6 shows the relation between the subsurface subsidence factor with different depth levels and MD/MH ratio. The parameters that the surface subsidence factor is 0.8 and the MD/MH ratio is 50, 100, 150, 200, and 250, respectively, are adopted in Figure 6.

As shown in Figure 6, the subsurface subsidence factor decreases with the increase of MD/MH ratio. The greater MD/MH ratio means the greater expandable scope of strata, which causes the decrease of subsidence factor. However, the decrease of subsidence factor with the depth increase is nonlinear, the decreasing tendency of which is fast firstly and slow lately. The subsurface subsidence factor approaches certain values finally. When the SSIF is greater, the decreasing tendency of the subsurface subsidence factor along with the increase of MD/MH ratio is more obvious.

With the increase of the MD/MH ratio, the differences of the subsurface subsidence factor among different depth levels decrease. This shows that, under the condition of a great MD/MH ratio, the accumulative vertical expansion value above the fractured zone is very small, the further strata expansion more focuses on strata near gob. In comparison, the vertical expansion has a more uniform distribution under the condition of a small MD/MH ratio. For an identical MD/MH ratio and equal depth interval, the difference value of the subsurface subsidence factor near gob is far greater than that far away from gob. These show that the change of the subsurface subsidence factor is concentrated in the vicinity of the gob and is slow when close to the ground. The greater the SSIF, the more obvious the decreasing tendency for different values of the subsurface subsidence factor on the equal depth interval.

4.2. Expansion Distribution (E-D) Factor. The parameter q_0 is the surface subsidence; similarly, the form of $(1 - q_0)$ could be called the overburden expansion factor. Researchers agree that the maximal vertical expansion is the decisive factor of surface subsidence. And the E-D factor just reflects the relationship between the overburden expansion factor and maximal vertical expansion value. Formula (10) indicates the relation between the E-D factor and the MD/MH ratio. The E-D factor embodies the comprehensive characteristic of overburden strata induced by mining operations, while the MD/MH ratio reflects the mining factor. Both are dimensionless values, having generality.

Formula (10) is a logarithmic function, and its asymptote function is as follows:

$$T_{\max}\varepsilon = 1 - q_0. \tag{11}$$

Based on the field data in Table 1, the scope of the maximum of the E-D factor ($T_{\max}$) is (2.84, 3.40). The E-D factor has an ultimate value, which does not increase infinitively with the increase of the MD/MH ratio.

Two aspects of reason cause the ultimate value existence for E-D factor. On the one hand, a great MD/MH ratio corresponds to the less maximal vertical expansion value [28]. The greater MD/MH ratio means less mining height or greater mining depth. Under these two conditions, the maximal vertical expansion is less. This is because the greater vertical stress caused by greater mining depth decreases the maximal vertical expansion value, while the less mining height has less dropping space to decrease the maximal vertical expansion value [24, 29, 31]. On the other hand, the surface subsidence factor decreases, and the surface expansion factor increases with the growth of the MD/MH ratio [25]. Considering the limitation of coal seam thickness, when the mining depth reaches a certain degree, the surface expansion coefficient tends to one, while the maximal vertical expansion value tends to a constant value [28, 32]. Thence, the ultimate value exists for the E-D factor.

As shown in Figure 7, the relation between surface subsidence and maximal vertical expansion value could be obtained from formula (11). In the figure, the vertical axis is the surface subsidence factor and the horizontal axis is the maximal vertical expansion value.

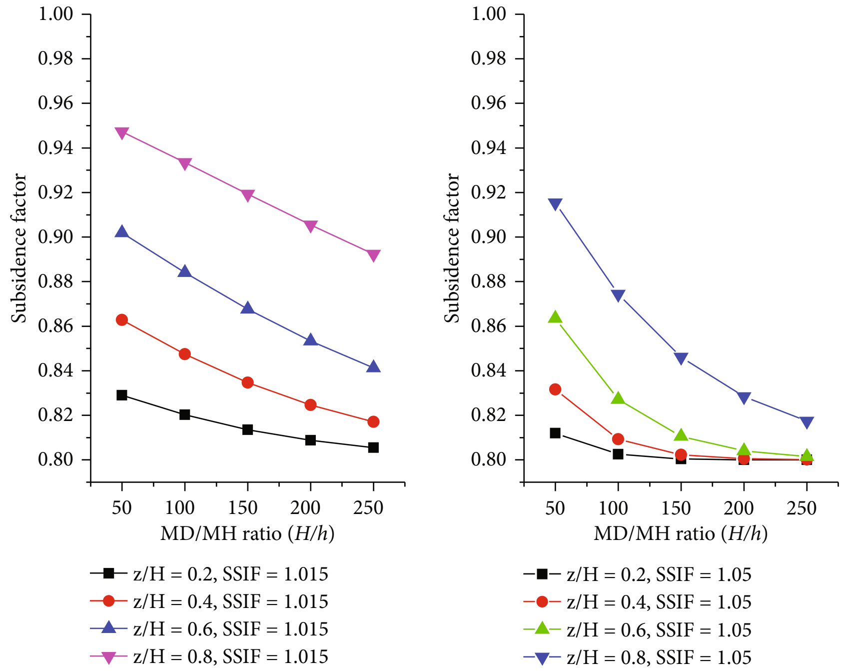

Figure 6: Relation between the subsurface subsidence factor and MD/MH ratio.

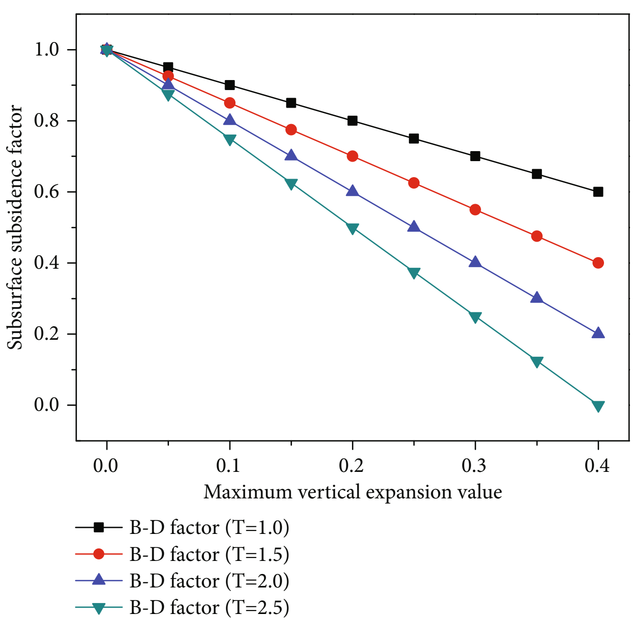

Figure 7: Relation between the surface subsidence factor and maximal vertical expansion value.

As shown in Figure 7, the surface subsidence factor linearly decreases along with the increase of maximal vertical expansion value. The decrease velocity of the surface subsidence factor with a less E-D factor is slower than that when the E-D factor is greater. In addition, along with the decrease of the E-D factor, the decreasing tendency of the surface subsidence factor is faster. This means that, for a condition of a great MD/MH ratio, the change of maximal vertical expansion coefficient has a greater influence on surface subsidence. This is because a great E-D factor corresponds to a greater MD/MH ratio and less surface subsidence factor [32], and the great MD/MH ratio represents the large scope of expansive strata. Thence, when maximal expansion value changes the identical percentage, the change of the surface subsidence factor with a large MD/MH ratio is greater.

5. Case Analyses

The subsurface subsidence was measured in the No. 94302 working face mined in Sihe No. 2 Coalmine, located in Shanxi Province, China [6]. The mining depth is 280-420 m. The mean value of the 9# coal seam in Sihe No. 2 Coalmine is 1.5 m of thickness, with 3° for dip angle of the coal seam.

As shown in Figure 8, the distance between 9# coal seam and 3# coal seam is 51 m. The multiple-position borehole extensometer was used for monitoring the subsidence of a roadway in 3# coal seam. And the monitoring borehole is located in the supercritical subsidence zone above the No. 94302 gob. Ten measuring points were arranged within the 2.3 m~47.5 m scope in the monitoring borehole.

The field data of the subsurface subsidence were analyzed with the two methods. The data were measured by borehole multipoint displacement meters. As shown in Figure 9, Li's method [15] and the proposed method were fitted to obtain the fitting curve and surface subsidence factor. The horizontal axis and vertical axis in the figure are depth level (z/H) and the subsidence factor.

As shown in Figure 9, the fitted value of SSIF and surface subsidence factor are, respectively, 1.06735 ± 0.02302 and 0.72247 ± 0.04039 through the proposed method. While

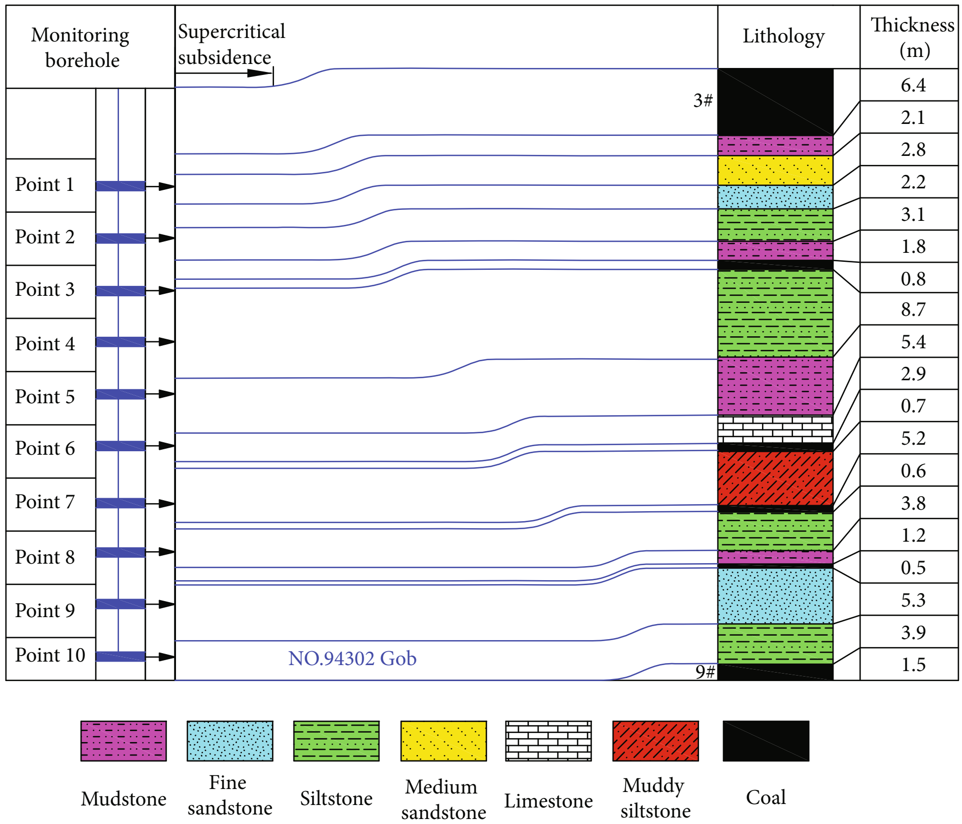

Figure 8: The geological condition and monitoring point arrangement.

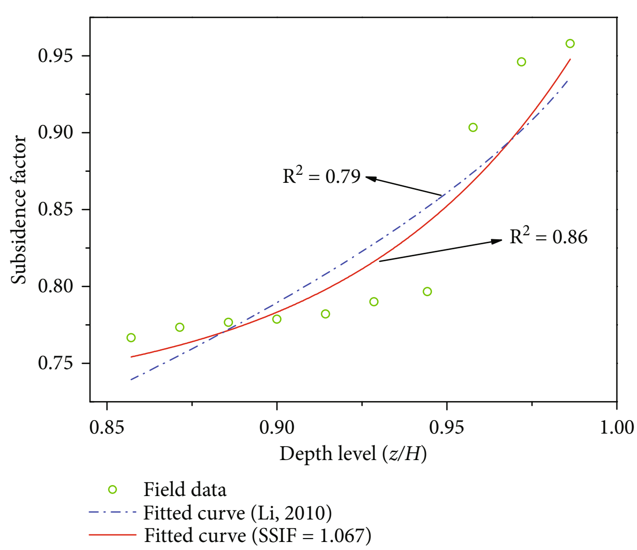

Figure 9: Curves of the subsurface subsidence factor fitted by different methods in Sihe No. 2 Coalmine.

the corresponding fitted values for Li's method are 0.59808 ± 0.13429 and 0.158 ± 0.267.

The mean and maximal values for relative error in this method are 0.13% and 5.7%, respectively, while the corresponding errors are 0.38% and 6.6% through Li's method. The smaller mean and maximum error show the higher precision of this method. The mean value and maximal value for relative error in this method are much lesser, showing that this method has higher precision.

It may be observed from the case that the mean error is less than 2%. However, the fitted value of the SSIF is farther greater than 1.0054 that was obtained via statistics. The chief reason is that underground coalmines have a great thickness of overburden strata and the MD/MH ratio exceeds 40. Thence, in practical application, the statistic for subsidence data of strata near the longwall gob is required to implement the fitting, or the parameters in the above-mentioned cases could be adopted to implement the rough estimate. In the next step, further study would be also required for the condition of multi-coal seam mining.

6. Conclusions

Such factors including the surface subsidence factor, maximal vertical expansion value, mining depth, and mining height were utilized to establish the distribution model of the subsurface subsidence factor above the longwall gob. Through data fitting, the correctness of the model is verified, and the conclusions as follows were obtained after analysis and discussion.

The assumption that the vertical expansion value for overburden strata above the longwall gob presents the exponential distribution along with a decrease from the gob to the ground is verified. The subsurface subsidence factor could be calculated by the formula $q_z = 1 - (1 - q_0)(a^{(z/H-1)(H/h)} - 1)/(a^{-(H/h)} - 1)$. In this formula, the SSIF could be obtained through parameter fitting and determine the distribution of the subsurface subsidence factor in the overburden strata. Different geological and mining conditions have different SSIF.

The SSIF, maximal vertical expansion value, and MD/MH ratio influence the subsurface subsidence factor. The greater SSIF means the less surface subsidence factor, and the distribution curve of the subsurface subsidence factor is more curve. The less the linearity for subsurface subsidence factor on each depth level decreases linearly with the increase of vertical expansion value. The influence degree of maximal vertical expansion value in strata approaching gob is farther greater than that in strata near the surface. The subsurface subsidence factor decreases with the increase of the MD/MH ratio. This is because the greater the MD/MH ratio means the greater expandable scope for strata and maximal vertical expansion value. When the SSIF, MD/MH ratio, and maximal vertical expansion value are greater, the strata expansion and subsidence furthermore focus on rock strata near the gob.

The expansion deformation (E-D) factor is defined as $(1 - q_0)/\mathcal{E}_0$ and is a dimensionless parameter, which embodies the relationship between subsurface expansion coefficient and maximal vertical expansion value and describes the comprehensive characteristic of overburden strata induced by mining operations. Based on the method proposed above, through the MD/MH ratio, the relation between surface subsidence and maximal vertical expansion value (bulking factor of a caving zones) is established under the condition of longwall mining. The MD/MH ratio and E-D factor follow the logarithmic relation. The E-D factor exists in the maximum, the range of which is (2.84, 3.40). Considering the limitation of coal seam thickness, when the mining depth reaches a certain degree, the surface expansion coefficient tends to one, while the maximal expansion value tends to a constant value. A study on the E-D factor shows that the surface subsidence factor with the greater MD/MH ratio is more sensitive to change of the maximal vertical expansion value.

The analysis for this case shows that the subsurface subsidence factor calculated by this method is provided with higher precision, and the mean error between the calculated value and measured value is less than 2%. Thence, in the practical application, it is necessary to correct the value of SSIF by adopting the data less than 40-time mining height or estimate roughly using the parameters in the above-mentioned cases.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Conflicts of Interest

The authors declare no conflict of interest. The authors identify and declare no personal circumstances or interests that may be perceived as inappropriately influencing the representation or interpretation of reported research results.

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