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Calculation Model of Overburden Subsidence in Mined-out Area Based on BOTDR Technology

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Abstract: With the increase of the coal consumption, the gob scale has become significantly large, increasing the risk of subsidence. Using the Brillouin optical time-domain reflectometer (BOTDR) technology, this paper studied the deformation and failure state of overburden above the gob. A overburden subsidence calculation model considering rock mechanical parameters based on the BOTDR was established. In addition, the influence of damage distribution parameters and rock particle contact parameters on the subsidence calculation model was discussed, and the spatial and temporal distribution rule of overburden subsidence was obtained. Taking Zhang Huaizhu working face in Zhangzhuang Coal Mine as an example, this paper verified the accuracy of the subsidence calculation model. The research results show that: The damage distribution parameters have little effect on the overburden subsidence calculation model. The subsidence maximum change caused by the tangential inclination of the particle contact surface in the bulking zone is 0.016 times the height of the bulking zone, while the subsidence maximum change caused by the friction coefficient is 0.046 times the height of the bulking zone. The overburden subsidence of Zhangzhuang Coal Mine has gradually been stabilized after deforming for one and a half year. The ground subsidence in the gob has a negative exponential relationship with time during research period. Compared the result of the subsidence calculation model proposed in this paper with the field monitoring value, it was found that the ground subsidence tendencies are basically the same, and the relative error is less than 8%. It indicates that the subsidence calculation model is reliable in calculating the overburden subsidence in the gob.

Keywords: distributed monitoring; overburden subsidence calculation; gob; optical fiber sensor; monitored strain

1 Introduction

The total consumption of global coal was about 7,864 million tons in 2012[1], which means that lots of large-scale gobs or mined-out areas were generated. Large-scale gobs not only affect the subsequent mining of coal, but also cause environmental problems such as the damage to farmland and transportation facilities, the pollution of water resources and unsafety of building structures. Therefore, accurately calculating the ground subsidence of the gob and timely grasping and evaluating the overburden deformation characteristics and surface stability of the gob play an important role in ensuring safe production of coal mines and solving ecological problems of mining areas.

At present, global positioning system (GPS) technology[2,3], synthetic aperture radar (SAR) technology[4], and interferometric SAR (InSAR) technology[5,6] have advantages of high spatial positioning, high deformation sensitivity, and high spatial resolution. They can monitor the continuous subsidence of the gob and obtain the surface subsidence distribution data. However, due to the increasing thickness of overburden during mining, complex multi-field interaction and a long-term disturbance to the overburden, the surface movement becomes concealed, complex and abrupt. The surface subsidence also has a nature of long-term development. Hence, it is hard to grasp the overburden subsidence rule only by using the above technologies for ground subsidence monitoring[7]. Other technologies also have their own limits. For example, using the time-domain reflectometry (TDR) technology and underground radon concentration detection technology to monitor the overburden subsidence in the gob is still in the validation stage[8, 9]. There are many interferences when applying the electrometric method[10], and the borehole sound velocity method is mostly used for auxiliary detection[11]. For CT detection method, it is difficult to realize distributed quantitative detection[12].

Distributed optical fiber sensor can obtain the strain and temperature distribution information of measurand fields along the fiber path in time and space simultaneously, and can realize long-term monitoring of structures[13, 14]. In addition, it has the advantages of light weight, small size, anti-electromagnetic interference. Brillouin optical time-domain reflectometer (BOTDR) is a distributed optical fiber strain sensor technology whose operation is based on Brillouin scattering. This equipment can measure continuous strain along an optical fiber over 10 km[15], and is used to detect deformations or predicted problems in large-scale structures. Therefore, distributed optical fiber sensor based on BOTDR is a better choice to monitor deformation of overburden rock in coal mines[16-18]. To obtain the deformation value of the overburden, it is common to integrate the optical fiber sensor monitored strain along the whole monitored range[16]. However, the integration method does not involve the relationship between rock mass mechanical parameters and the subsidence stage of the overburden, moreover, the uneven deformation of the overburden rock mass is not considered.

In this paper, the BOTDR technology was adopted, the deformation and failure characteristics of the overburden in the gob was studied, and a "zoning" method based on the mechanical properties of the overburden rock and soil was proposed. Additionally, this paper established a subsidence calculation model based on the measured strain data, and discussed the influence of damage distribution parameters and particle contact parameters on the calculation model. Combining the distribution of overburden strain in the mined-out area of Zhang Huaizhu working face of Zhangzhuang Coal Mine, the paper verified the reliability of the proposed calculation model. The research results can provide theoretical calculation basis for understanding the overburden subsidence timely and spatially.

2 Model for calculating overburden subsidence in the gob based on BOTDR

2.1 Overburden zoning

According to rock-soil body properties and the characteristics of overburden subsidence caused by mining, stabilized overburden strata after movement are generally divided into the caving zone, fractured zone, bending zone and unconsolidated layers[19]. The rock mass in the caving zone is completely broken and filled with rock blocks, which contributes most to the surface subsidence above the gob. The rock mass in the fractured zone is full of fully developed fractures. While the rock mass of the bending zone has good integrity, and is divided into a microseismic active area and an elastic deformation area based on the rock deformation state[20]. The microseismic active area is in direct contact with the fractured zone and contains rock fractures and other types of damage; therefore, the damage factor can be used to represent the fracture development state in the microseismic active area. The elastic deformation area is under the elastic deformation stage in the bending zone. The unconsolidated layers is comprised of the rock and soil, and it can be assumed that only elastic deformation occurred like the elastic deformation area in the bending zone.

For the convenience of the subsidence calculation model derivation, the overburden was divided into three new parts according to the state and deformation characteristics of overlying rock and soil above the gob, that is, bulking zone (caving zone) based on the broken rock mass, damage zone (fracture zone and microseismic active area) based on the fractured rock mass, and continuous deformation zone (elastic deformation area and unconsolidated layers) based on continuous rock mass. The schematic diagram of overburden deformation zones in coal seam is shown in Fig.1.

The red line in Fig.1 is an example of the optical fiber strain sensor’s layout in overburden. It is noted that the strain data of overburden by optical fiber strain sensor is in one direction along the optical fiber. If we lay a vertically oriented fiber within the overburden of the goaf, then it is reasonable to assume that the strain data returned by the fiber is vertical strain[13].

2.2 Simplify

2.2.1 distributed monitoring scheme for overburden in the gob

To explain the basis of the simplified calculated model clearly, a brief description of the optical fiber monitoring scheme in the mining overburden is necessary: first drill a hole into the ground along the gob of the coal mine, implant an optical cable made of glass fiber reinforced plastics (GFRP) into the borehole slowly, and then pour concrete grout into the hole to seal. In order to ensure the filling back material concrete grout deforms together with the surrounding rock, it is better that the elastic modulus of filling material is larger than the surrounding rock[21]. In addition, adopting a screw-like package design for an embeddable distributed optical fiber strain sensor also can improve the deformation coupling degree between them[22]. The schematic diagram of the layout and monitoring of the optical fibre cable in the overburden is shown in Fig.2.

2.2.2 Assumptions and the final simplified model

According to the principle of BOTDR, it can be considered that strain sensors are distributed every sampling interval along the fiber, and the interval is usually between 0.05m and 1m[23,24]. Because of the existing of the void, cracks and other damage, the deformation of overburden, especially in caving zone and damage zone, is unevenly. As the optical fiber strain sensor monitors only at specific monitored points, the returned strain is somewhat different from the rock mass strain outside the monitoring point. When calculating the subsidence, it is required to accumulate the strain within the height range. If the strain data returned from the monitoring point is considered the same as the overall deformation of the rock, a large cumulative error will occur. In this study, we use the strain outside the monitoring point ε_r and the strain at the monitoring point ε_m to distinguish these two kinds of strain.

The calculation model is simplified, as shown in Fig.3, where λ is the spatial sampling interval.

The strain outside the monitoring point i is considered as the average strain of one spatial resolution λ as shown in Fig.3.

The interaction between the optical fiber and the monitored rock has been studied by many researches[21,25,26], and to simply the model, it is assumed that the data returned from optical fiber sensor is the rock mass strain at the monitoring point. To get a general calculated method, the other following assumptions also need be claimed:

The stain returned by the optical fiber sensor is vertically;

The monitored rock mass, filling material and optical fiber deform together;

The stress near each monitoring point is equal;

When implanting the optical fiber, the mine below the drilling hole was excavated.

2.3 Subsidence calculation model of different overburden deformation zones in the gob

2.3.1 Subsidence calculation model of rock mass in bulking zone

As known from sub-section 2.2.2, the strain at the monitoring point and the strain of the whole rock mass should calculate separately.

A constitutive model of broken rock mass was adopted to reflect the stress-strain relationship of the rock mass at the strain monitoring point[27,28]:

$$\sigma_z^b = \frac{E\varepsilon_m^b}{1 - \varepsilon_m^b / \varepsilon_{\max}} \tag{1}$$

where σ_z^b is the vertical strain of rock mass in the bulking zone; E is the elastic modulus of rock mass; ε_m^b is the strain at the monitoring point in the bulking zone; $\varepsilon_{\max}$ is the maximum strain of the rock mass along the vertical direction, and it can be calculated by the initial bulking coefficient K_0 as follows[29,30]:

$$\varepsilon_{\max} = 1 - \frac{1}{K_0} \tag{2}$$

Since the coal mine was excavated and the rock mass has been broken, the deformation in bulking zone has two main forms: the compression deformation of the rock body itself and the volumetric compression of the rock mass void caused by arrangement and distribution changes of rock blocks. When the stress applied to the broken rock fragments can't cause sliding deformation, the rock particles only undergo self-compressive deformation. When the stress is big enough to cause sliding friction between particles, sliding deformation between rock particles and self-compressive deformation of the rock mass would occur simultaneously or only sliding deformation. Compressive deformation of the broken rock mass can be represented by three kinds of components in a parallel form, as shown in Fig.4.

Fig.4 shows that the deformation of the broken rock mass can be simplified into three forms: Component Ⅰ. The compressive deformation of rock particles is simplified as an elastic element; Component Ⅱ. When the deformation of the rock body and the sliding friction occur together, the deformation is then simplified as an elastic element and a friction plate which are connected in series; ComponentⅢ. The sliding friction between the rock particles is simplified as a friction plate. The three components are connected in parallel, and we can obtain the relationship of strain and stress with each contact form:

$$\begin{cases} \sigma_z^b = \sigma_{E'} + \sigma_\mu \\ \varepsilon_r^b = \varepsilon_1 = \varepsilon_2 = \varepsilon_3 \end{cases} \tag{3}$$

where σ_z^b is vertical stress of the rock in the bulking zone; $\sigma_{E'}$ is the total stress of the elastic element in component Ⅰ and component Ⅱ; σ_μ is the total stress of the sliding plate in component Ⅱ and componentⅢ; ε_r^b is vertical strain of the rock in the bulking zone; ε_1 is the strain applied to component Ⅰ; ε_2 is the strain applied to component Ⅱ; ε_3 is the strain applied to component III.

Since the elastic component of the model represents the rock block deformation, the damage influence need be considered. According to damage mechanics, the effective elastic modulus of each rock particle can be expressed by the damage factor[31]:

$$E' = (1-D)E \tag{4}$$

where E' is the effective elastic modulus; D is the damage factor.

The stress applied to the elastic component and the friction plate in Fig.4 (c) can be calculated by:

$$\begin{cases} \sigma_{E'} = (1-D)E\varepsilon_r^b \\ \sigma_\mu = \dfrac{1}{2}\mu\sigma_z^b \sin(2\theta) \end{cases} \tag{5}$$

where θ is the angle between the tangent of the sliding friction surface and the horizontal direction (shown in Fig.4 (b)), named contact surface angle in the following discussion; μ is the friction coefficient.

By substituting Eq.(5) into Eq.(3) and then into Eq.(1), the relationship between the vertical strain of the rock mass in the bulking zone ε_r^b and the strain at monitoring points in the bulking zone ε_m^b can be expressed by:

$$\varepsilon_r^b = \frac{\varphi(K_0-1)\varepsilon_m^b}{(1-D)\left[(1-\varepsilon_m^b)K_0-1\right]} \tag{6}$$

where $\varphi = 1-\frac{1}{2}\mu\sin(2\theta)$, is the contact parameter of rock particles, and is related to the contact surface inclination and roughness.

The subsidence of the overburden rock mass including two parts: the compression of the rock mass itself which can be gotten through Eq.(6) and the displacement with the lower strata. Therefore, the subsidence of the bulking zone can be obtained by adding all the strata deformation from the bottom of the caving zone to this certain depth. The formula for calculating the subsidence of overburden at height h_1 in the bulking zone can be expressed by:

$$W_b\left(h_1\right)=\sum_{k=1}^{n}\frac{\lambda\varphi\left(K_0-1\right)\varepsilon_{mk}^{b}}{\left(1-D\right)\left[\left(1-\varepsilon_{mk}^{b}\right)K_0-1\right]} \tag{7}$$

where $W_b\left(h_1\right)$ is the subsidence of the rock mass in the bulking zone when the overburden height is h_1, and at this time h_1 falls within the height range of the bulking zone; n is the maximum number of optical fibre sensor's monitoring points within height h_1; λ is the space sampling interval of the optical fibre sensor; ε_{mk}^{b} is the strain value monitored at the *k*th monitoring point in the bulking zone.

2.3.2 Subsidence calculation model of rock mass in damage zone

The same as bulking zone, because of the uneven deformation, the strain at the morning point and the strain of the rock mass at the damage zone should calculate separately. The rock strain at the monitoring point is considered as elastoplastic strain, then it can be calculated by:

$$\varepsilon_m^d=\varepsilon_z^e+\varepsilon_z^p \tag{8}$$

where ε_m^d is the strain at the morning point in the damage zone; ε_z^e is vertical elastic strain of the rock mass at the monitoring point; ε_z^p is vertical plastic strain of the rock mass at the monitoring point.

Assume that the deformation of the rock mass in the damage zone conforms to plastic total deformation theory, Eq.(8) can be rewritten as:

$$\varepsilon_m^d-\varepsilon_z^e=\frac{\varepsilon_i}{\sigma_i}\left[\sigma_z^d-\frac{1}{2}\left(\sigma_x^d+\sigma_y^d\right)\right] \tag{9}$$

where σ_i is the stress strength; ε_i is the plastic strain strength; σ_x^d, σ_y^d and σ_z^d are the stress of rock mass in the damage zone at x, y, and z direction, respectively.

Elastic strain in Eq.(9) of the rock mass in the damage zone can be expressed by:

$$\varepsilon_z^e=\frac{1}{E}\left[\sigma_z^d-\frac{1}{2}\left(\sigma_x^d+\sigma_y^d\right)\right] \tag{10}$$

When damage occurs at the rock mass due to cracks, pores and other structures, the rock mass strain can be expressed by the constitutive equation of the damaged rock:

$$\varepsilon_r^d=\frac{1}{\left(1-D\right)E}\left[\sigma_z^d-\frac{1}{2}\left(\sigma_x^d+\sigma_y^d\right)\right] \tag{11}$$

where ε_r^d is the vertical strain in the damage zone.

By combining Eq.(9), Eq.(10), and Eq.(11), the relationship between the rock mass strain ε_r^d and the strain at the monitoring point ε_m^d can be expressed by:

$$\varepsilon_r^d = \frac{\sigma_i}{(1-D)(E\varepsilon_i + \sigma_i)}\varepsilon_m^d \tag{12}$$

The same as bulking zone, according to Eq.(12), the model for calculating the subsidence of the rock at height h_2 in the damage zone can be expressed by:

$$W_d(h_2) = W_b + \sum_{k=N+1}^{m} \frac{\lambda\sigma_i}{(1-D)(E\varepsilon_i + \sigma_i)}\varepsilon_{mk}^d \tag{13}$$

where $W_d(h_2)$ is overburden subsidence in the damage zone when the overburden height is h_2, and h_2 falls within the height range of the damage zone; W_b is total subsidence of the bulking zone, which can be calculated by Eq.(7); N is the total number of monitoring points in the bulking zone; m is the maximum number of optical fiber sensor's monitoring points within height h_2; ε_{mk}^d is the strain value monitored at the *k*th monitoring point in the damage zone.

2.3.3 *Subsidence calculation model of rock mass in the continuous deformation zone*

Because we assumed the rock-soil body in elastic deformation zone and unconsolidated layers is elastic body, the deformation in continuous deformation zone is evenly. In that case, the strain can reflect that of the whole rock mass in continuous deformation zone. The model for calculating the subsidence at height h_3 in the continuous deformation zone can be expressed by:

$$W_c(h_3) = W_b + W_d + \sum_{k=M+1}^{p} \lambda\varepsilon_{mk}^c \tag{14}$$

where $W_c(h_3)$ is overburden subsidence in the continuous deformation zone when the overburden height is h_3, and h_3 falls within the height range of the continuous deformation zone; W_d is the total subsidence of the damage zone, which can be calculated by Eq.(13); M is the total number of monitoring points in the bulking zone and damage zone; p is the maximum number of monitoring points in the continuous deformation zone when the overburden height is h_3; ε_{mk}^c is the strain at the monitoring point in continuous deformation zone at the *k*th monitoring point.

3 State parameters of overburden subsidence calculation model

3.1 Change characteristics of the damage factor

3.1.1 Calculation of the damage factor

The damage factor is related to the degree of damage and deformation of the rock mass. Conventionally, the internal defects of microelement of rock are subject to obey the statistical law and obey the two-parameter Weibull distribution[32,33]. The damage factor can be defined as:

$$D = 1 - \exp\left[-\left(\frac{\varepsilon_m}{\varepsilon_0}\right)^{m_0}\right] \tag{15}$$

where ε_m is the overburden strain measured by the optical fibre sensor; ε_0, m_0 is Weibull distribution parameters, which can be gotten from the stress-strain curve fitting.

ε_0 reflects the strain value of the rock, which is proportional to the mean value of the strain, and it also increases along with the increase of the peak strain in the stress-strain curve. m_0 reflects the concentration of strain distribution of rock microelements, and the bigger m_0 is, the more concentrated the strain distribution becomes. m_0 is also referred to as the homogeneity index[34].

By substituting Eq.(15) into the constitutive equation of damaged rock mass, a new constitutive function of the damaged rock based on the Weibull distribution is obtained:

$$\sigma_z - \mu\left(\sigma_x + \sigma_y\right) = E\varepsilon_z \exp\left[-\left(\varepsilon_m / \varepsilon_0\right)^m\right] \tag{16}$$

In order to find the magnitude of distribution parameters, logarithmic transformation is applied to Eq.(16). Thus it is rewritten as:

$$m \ln \varepsilon_z - m \ln \varepsilon_0 = \ln\left\{-\ln \frac{\sigma_z - \mu\left(\sigma_x + \sigma_y\right)}{E\varepsilon_z}\right\} \tag{17}$$

According to the post-peak data of the stress-strain curve in the triaxial compression test of the rock mass, the value of ε_0 and m_0 can be obtained by linear fitting of Eq.(17).

Take sandstone as an example, to obtain its stress and strain data, a software named PFC3D based on particle discrete element method is adopted to simulate a conventional triaxial compression test. The parameters used in this numerical simulation test are as follows: elastic modulus is 2.29×10^3 MPa; peak strength is 190 MPa when confining pressure is 8 MPa; passion rate is 0.230[35]. After parameter calibration, discrete particle simulation in the conventional triaxial compression test was carried out to study stress-strain curve of sandstone when the confining pressure is 2 MPa, 8 MPa, 14 MPa, 20 MPa, 26 MPa and 32 MPa.

Fig.5 shows the results of triaxial compression tests of sandstone under different confining pressures, and P_0 represents the confining pressure.

As shown in Fig.5, as the confining pressure increases, the peak strength and peak strain of the rock mass will also increase, while the concentration of the stress-strain curve will decrease.

The post-peak data of the sandstone stress-strain curve under different confining pressures is fitted by linear fitting according to Eq.(17). The change characteristics of m_0, ε_0 and ε_{peak} under different confining pressures are shown in Fig.6.

As shown in Fig.6, due to the concentration changes of the stress-strain curve concentration under different confining pressures, m_0 decreases exponentially with the increasing of the confining pressure, and their fitting function is $m_0 = \exp\left(1.83 - 0.104 p_0 + 0.0015 {p_0}^2\right)$, coefficient of determination R^2 is 0.99. When the confining pressure reaches 20 MPa, m_0 gradually stabilizes. ε_0 and ε_{peak} increase linearly with the increasing of the confining pressure, and their fitting functions are $\varepsilon_0 = 0.097 + 0.0034 p_0$ and $\varepsilon_{peak} = 0.090 + 0.0017 p_0$, whose coefficients of determination R^2 are 0.99 and 0.98, respectively. What's more, ε_0 is always greater than ε_{peak}.

3.1.2 Influence of distribution parameters on the subsidence calculation model of the bulking zone

By substituting Eq.(15) into the strain calculation function Eq.(6) of the bulking zone, the following equation can be obtained:

$$\varepsilon_r^b = \frac{\varphi\left(K_0 - 1\right)\varepsilon_m^b}{\exp\left[-\left(\varepsilon_m^b / \varepsilon_0\right)^{m_0}\right]\left[\left(1 - \varepsilon_m^b\right)K_0 - 1\right]} \tag{18}$$

Assume that the contact parameter of rock particles φ is 0.75, the bulking factor K_0 is 1.3, and the strain at the monitoring point of the bulking zone is 0.0005, 0.0025, 0.0045, 0.0065, 0.0085, 0.0105, 0.0125 and 0.0145, respectively. In order to study the influence of distribution parameters on the precision of subsidence calculation in the bulking zone, m_0 is fixed as 3 when discussing the influence of ε_0, and ε_0 is fixed as 0.0045 when studying the influence of m_0. Fig.7 shows the curves of ε_r^b changing with ε_0 and m_0 respectively.

Fig.7(a) shows that when $\varepsilon_0 \geqslant \varepsilon_m^b$, the maximum change value of the strain ε_r^b is 0.00198 as ε_0 increases from ε_m^b to 0.0752. Hence, ε_0 has little influence on ε_r^b, and according to Eq.(7), it also has little influence on subsidence calculation results. When $\varepsilon_0 < \varepsilon_m^b$, except for $\varepsilon_m^b = 0.0005$ (As the data of $\varepsilon_0 < \varepsilon_m^b$ when $\varepsilon_m^b = 0.0005$ is less, there is no abrupt phase of the calculated strain in the bulking zone ε_r^b), ε_r^b decreases sharply at the initial stage of ε_0, and its sensitivity to ε_0 is high. Hence, in this situation, the accuracy of ε_0 has great influences on the subsidence calculation results. As shown in Fig.7(b), when $\varepsilon_0 \geqslant \varepsilon_m^b$, strain in bulking zone ε_r^b is almost constant with the change of m_0. The maximum change of the strain ε_r^b is 0.0014 as m_0 changes from 1 to 91, which indicates that the change of m_0 at this situation has little effect on the strain ε_r^b, and thus has little effect on the final subsidence calculation results. When $\varepsilon_0 < \varepsilon_m^b$ and m_0 increases to a certain value, the strain in the bulking zone ε_r^b increases sharply, especially when $\varepsilon_m^b \geqslant 0.0105$, the strain ε_r^b changes almost vertically in Fig.7(b), and at this time, the accuracy of m_0 has a huge impact on the subsidence calculation results.

Because of the mined-out stage of the gob, the secondary broken of the rock particles after rock mass breaks is not considered. According to Fig. 6 ε_0 is always larger than ε_{peak}. It ought to be noted that from the derivation process of the subsidence calculation model of the bulking zone, D is the damage factor of the rock mass blocks rather than the entire rock mass in the bulking zone. As the overburden subsidence after mining is in a stable stage and no rock particle at the monitoring point breaks again, the strain at the monitoring point in the bulking zone ε_m^b will always be smaller than the peak strain ε_{peak} of the rock body, and also smaller than ε_0. Hence, according to Fig.6, the accuracy of distribution parameters ε_0 and m_0 have little effect on the subsidence results of the bulking zone. In that case, we can let $\frac{\varepsilon_{mk}^b}{\varepsilon_0}=\left|\varepsilon_{mk}^b\right|$ (ε_0 and ε_{mk}^b always has the same directions), $m_0=1$, and the model for calculating the overburden subsidence in the stable stage in the bulking zone can be simplified as:

$$W_b\left(h_1\right)=\sum_{k=1}^{n}\frac{\lambda\varphi\left(K_0-1\right)\varepsilon_{mk}^b}{\exp\left(-\left|\varepsilon_{mk}^b\right|\right)\left[\left(1-\varepsilon_{mk}^b\right)K_0-1\right]} \tag{19}$$

3.1.3 Influence of distribution parameters on the subsidence calculation model of the damage zone

By substituting Eq.(15) into strain calculation function of the damage zone Eq.(12), then we can get the equation as follows:

$$\varepsilon_r^d=\frac{\sigma_i}{\exp\left[-\left(\varepsilon_m^d/\varepsilon_0\right)^{m_0}\right]\left(E\varepsilon_i+\sigma_i\right)}\varepsilon_m^d \tag{20}$$

In order to study the influence of distribution parameters on subsidence calculation results of the damage zone, fix the values of the parameters are as follows: $\sigma_i=3\ \mathrm{MPa}$, $\varepsilon_i=0.075$ and the strain at monitoring points in the damage zone ε_m^d are 0.0005, 0.0025, 0.0045, 0.0065, 0.0085, 0.0105, 0.0125 and 0.0145, respectively. When analyzing the influence of ε_0 on ε_r^d, fix $m_0=3$. When analyzing the influence of m_0 on ε_r^d, fix $\varepsilon_0=0.0045$. Fig.8 shows the changes of calculated strain in the damage zone ε_r^d along with ε_0 and m_0.

As shown in Fig.8, similar to the bulking zone, when $\varepsilon_0 \geqslant \varepsilon_m^d$, the maximum change of the strain in the damage zone ε_r^d is 4.97×10^{-5} as ε_0 increases from ε_m^d to 0.0752, while as m_0 increases from 1 to 91, the maximum change of ε_r^d is 3.72×10^{-6}. Therefore, when $\varepsilon_0 \geqslant \varepsilon_m^d$, combining with Eq.(13), we can find that the results of subsidence calculation are insensitive to the changes of ε_0 and m_0, and the accuracy of ε_0 has little influence on the final results of subsidence calculation. When $\varepsilon_0<\varepsilon_m^d$, similar to the bulking zone, except for $\varepsilon_m^d=0.0005$, the calculated strain of the damage zone ε_r^d decreases sharply in turn at the initial stage of ε_0, and under this situation, its sensitivity to ε_0 is high, which means the accuracy of ε_0 has a large impact on the final calculation results of subsidence. As for m_0 , when $\varepsilon_0 < \varepsilon_m^d$, the relationship curve of ε_r^d and m_0 has the tendency of steady increase followed by a rapid increase, and the bigger the ε_m^d is, the smaller the m_0 at the catastrophe point is. Thus, the larger the monitored strain in the damage zone ε_m^d is, the smaller the value of m_0 at the high sensitivity area of the strain in the damage zone becomes. Hence, when $\varepsilon_0 < \varepsilon_m^d$, the subsidence calculation result is sensitive to the change of m_0 .

The rock mass in the damage zone has not completely broken yet and still has the ability to withstand stress, so it is reasonable to assume that ε_m^d is always less than ε_0 like the bulking zone. Therefore, it can be considered that the accuracy of the distribution parameters ε_0 and m_0 under discussion has little effect on the subsidence calculation results of the damage zone. When the strain at monitoring points is less than the distribution parameter ε_0, we can fix parameters: $\frac{\varepsilon_{mk}^d}{\varepsilon_0} = \left|\varepsilon_{mk}^d\right|$ (ε_0 and ε_{mk}^d always has the same direction), $m_0 = 1$ and obtain a simplified model for calculating the subsidence of the damage zone:

$$W_d\left(h_2\right) = W_b + \sum_{k=N+1}^{m} \frac{\lambda \sigma_i}{\exp\left(-\left|\varepsilon_{mk}^d\right|\right)\left(E\varepsilon_i + \sigma_i\right)} \varepsilon_{mk}^d \tag{21}$$

3.2 Influence of particle contact parameter in the bulking zone on subsidence calculation model

According to Eq.(6), the vertical strain of the rock mass in the bulking zone ε_r^b is proportional to the particle contact parameter φ. This paper analyzed the influence of the contact parameter on the subsidence calculation model from two perspectives: contact surface angle θ and friction coefficient μ .

3.2.1 Influence of contact surface angle θ on the subsidence calculation model

In order to study the influence of changes of contact surface angle θ on the subsidence calculation model, we fix bulking coefficient K_0 as 1.3, friction coefficient μ as 0.35, and distribution parameters ε_0 and m_0 as 0.0045 and 3, respectively. Fig.9 shows the influence of changes of the contact surface angle on the subsidence calculation model under different monitored strain conditions.

According to Fig.9, the strain of the bulking zone ε_r^b is symmetrical along the contact surface angle of 90° . As θ increases within the range of 0~180° , ε_r^b and φ decrease at first and then increase, which reach the maximum when θ is 0° and 180° and reach the minimum when θ is 90° . When $\varepsilon_m^b \leqslant 0.0025$, the change of θ has little effect on ε_r^b, and under this situation, when $\varepsilon_m^b = 0.0025$, ε_r^b changes the most, being 0.002. When $\varepsilon_m^b > 0.0025$, changes of θ affect ε_r^b. The bigger the ε_m^b is, the bigger the curvature is, and the more sensitive of ε_r^b to changes of θ is. When $\varepsilon_m^b = 0.0045$, ε_r^b undergoes the maximum change, being 0.016. Therefore, the maximum influence of the surface contact angle of rock particles on model calculation results is 0.016 h_b (h_b is the height of the bulking zone). Hence, when calculating subsidence of the bulking zone by using the model, the accuracy of θ needs to be considered.

Due to the large amount of θ and the difficulty of monitoring on field, it is assumed that θ follows a normal distribution in the range [0°, 180°], that is, $\theta \sim N\left(90^0, \left(30^0\right)^2\right)$. Then the mean value of θ can be obtained as follows:

$$\bar{\theta} = \int_0^{180} \frac{1}{569.2} \exp\left[\frac{(\theta - 90)^2}{1800}\right] \mathrm{d}\theta \tag{22}$$

Hence, currently, $\varphi = 1 - 0.463\mu$.

3.2.2 *Influence of friction coefficient μ on the subsidence calculation model*

In order to study the sensitivity of the subsidence calculation model to changes of the friction coefficient μ , we let $K_0 = 1.3$, $\theta = 90^\circ$, $\varepsilon_0 = 0.0045$ and $m_0 = 3$. Fig.10 shows the influence of friction coefficient changes on the subsidence calculation model under different monitoring point strain ε_m^b conditions.

According to Fig.10, φ and ε_r^b decrease linearly with the friction coefficient, and the decreasing rate increases with the strain at monitoring points. When $\varepsilon_m^b = 0.0015$, the change of ε_r^b is smallest with the increase of the friction coefficient, being 0.002. When $\varepsilon_m^b = 0.0045$, the influence value of the contact parameter on ε_r^b is getting the maximum value, being 0.046. Hence, the maximum influence value of the rock particle friction coefficient on the calculation model is $0.046\,h_b$. φ decreases linearly with the contact surface friction coefficient μ, and the value of it is always in the range [0.5, 1.0].

3.3 The final calculation model after parameter analysis

After the analysis of the damage factor and the contact parameters, a simplified final calculation model of the overburden subsidence is obtained:

$$W(h)=\begin{cases} \sum\limits_{k=1}^{n} \dfrac{\lambda(1-0.463\mu)(K_0-1)\varepsilon_{mk}^b}{\exp\left[-\left|\varepsilon_{mk}^b\right|\right]\left[\left(1-\varepsilon_{mk}^b\right)K_0-1\right]} & 0 < h \leqslant H_1 \\ W(H_1)+\sum\limits_{k=N+1}^{m} \dfrac{\lambda\sigma_i}{\exp\left[-\left|\varepsilon_{mk}^d\right|\right](E\varepsilon_i+\sigma_i)}\varepsilon_{mk}^d & H_1 < h \leqslant H_2 \\ W(H_2)+\sum\limits_{k=M+1}^{p} \lambda\varepsilon_{mk}^c & H_2 < h \leqslant H_3 \end{cases} \tag{23}$$

where H_1 is the height of the boundary between the bulking zone and the damage zone; H_2 is the height of the boundary between the damage zone and the continuous deformation zone; H_3 is the height of the total overburden.

4. Field test of overburden subsidence in the gob of Zhanghuaizhu working face in Zhangzhuang Coal Mine

4.1 Distributed monitoring at the engineering site

4.1.1 A survey of test site

Zhangzhuang Coal Mine is located in the middle of the Zhahe synclinorium in Huaibei Coalfield, which is 8 kilometers northeast of Huaibei City, Anhui Province, China. Take Zhang Huaizhu working face in Zhangzhuang Coal Mine as an example, BOTDR technology was used to study the subsidence calculation methods and subsidence characteristics of overburden above the gob. The coal seam thickness of Zhang Huaizhu working face is 3.2 m, and its burial depth is 240.33 m ~ 243.53 m. The stratum layer distribution and physical and mechanical parameters of Zhangzhuang coal mine are shown in Table 1.

4.1.2 Distributed monitoring scheme for overburden in the gob

In the test, the N8511 BOTDR instrument was used to test the strain distribution information of the overburden over time, and the optical fiber is implanted as the method expressed in subsection 2.2.1. Table 2 shows the main technical performance indicators of the N8511 BOTDR instrument.

In order to grasp the on-site data of ground subsidence above the gob and verify the proposed subsidence calculation model, the hydrostatic levelling line based on fiber Bragg grating (FBG) is set from north to south at 10 m west of the drilling hole. The distribution of optical fiber monitoring point and hydrostatic levelling monitoring line in the mining area of Zhangzhuang Coal Mine is shown in Fig.11.

Fig.12 shows the site situation when lowering the optical fiber sensor in the drilling hole.

4.1.3 Overburden monitoring results by distributed optical fiber cable

The mining of coal seam of Zhang Huaizhu working face in Zhangzhuang Coal Mine was finished in April 2011. In order to grasp the characteristics of overburden deformation and ground subsidence tendency caused by the mining, we completed the layout of the optical fiber cable before August 9, 2013, and then performed the first test. Fig.13 shows the vertical monitored strain distribution of overburden rock above the gob during the period from October 2, 2013 to December 10, 2014.

Combined with the recommended equation of each zone’s height[36] and the vertical strain distribution characteristics in Fig.13, the coal seam overburden in Zhang Huaizhu working face is most likely can be divided into four zones from bottom to top: the caving zone, with a burial depth of 197 ~ 240 m; the fractured zone, with a burial depth of 160 ~ 197 m; the bending zone, with a burial depth of 65 ~ 160m; and the unconsolidated layers, with a burial depth of 0~65 m. Among them, the range of the elastic deformation area of the bending zone is 65 ~ 155 m, and the range of the seismic active area is 155 ~ 160 m.

It is indicated from Fig.13 that the rock mass in the caving zone has been broken, the compression deformation has not yet stabilized, so the strain changed greatly. There were many unusual deformation areas in the fractured zone. Although the rock mass has not yet settled and stabilized totally, the strain value was not large. The overall strain value of the bending zone was small, indicating that coal mining has a limited impact on this zone. Due to the shallow burial depth of unconsolidated layers, the test data provided by the optical cable was susceptible to temperature. Additionally, affected by the looseness of this zone easily, the bonding between the optical cable and the surrounding soil layer was weak after drilling and sealing, causing the heavy fluctuation of the monitored data. Therefore, the strain monitoring results can not accurately reflect the deformation characteristics of unconsolidated layers. It is not appropriate to directly use the monitored strain of the test data when calculating the subsidence of these layers. For the application of the calculation model, these four zones of the overburden was divided again into three deformation zones: a bulking zone with a burial depth of 197 m ~ 240 m, a damage zone with a burial depth of 155 m ~ 197 m and a continuous deformation zone with a burial depth of 0 ~ 155 m.

4.2 Determination of calculation model parameters

4.2.1 Initial bulking coefficient

The initial bulking coefficient of the rock mass in the bulking zone can be obtained as[37]:

$$K_0=\frac{c_1 h+c_2}{100}+1 \tag{23}$$

where c_1 and c_2 is strength coefficients of strata; h is the mining height.

According to the stratum properties in the bulking zone of Zhang Huaizhu working face, the strength coefficients c_1 and c_2 are 4.7 and 19[29,38], respectively. Hence, the initial bulking coefficient K_0 of the rock mass in this test is 0.33.

4.2.2 Particle contact parameters of rock mass in the bulking zone

Assume that the angle between the particle contact surface and the horizontal direction obeys the normal distribution, the strata in the bulking zone is mudstone interbedded with sandstone and the friction coefficient is fixed as 0.32, then its particle contact parameters of rock mass φ is 0.795.

4.2.3 Damage distribution parameters

The range of the bulking zone and damage zone in the overburden of Zhang Huaizhu working face is: 155 m ~ 240 m, including 3 rock layers, which are layer (7), (8), and (9). To obtain the subsidence calculation parameters of the damage zone, estimate the average values of the confining pressures of the (7), (8), and (9) layers of the bulking zone and damage zone according to formula $P_0=\eta\sum\gamma h_z$ (h_z is the height of each layer; η is the ratio of horizontal in-situ stress to vertical in-situ stress, and we can estimated that this ratio in Huaibei region of China is 1.9[39].), use the discrete particle simulation method to obtain the stress-strain curve of the three layers under the confining pressures, and apply the linear fitting to Eq.(17). The damage parameters of overburden in the gob are shown in Table 3.

4.2.4 Calculation of stress strength and plastic strain strength in the damage zone

As the subsidence calculation of overburden above the gob is related to the depth of coal seam, plastic strain and elastic strain in the vertical direction of overburden, and is independent of shear strain[20], the effective stress can be calculated as follows:

$$\sigma_i = \sqrt{(\eta - 1)}\sigma_z \tag{24}$$

where σ_z is the average vertical stress of the strata in the damage zone, which can be calculated according to the burial depth and bulk density of the rock layer in Table 1. Therefore, the effective stresses of layer (7) and (8) of the overlying strata in the damage zone of Zhang Huaizhu working face are calculated to be 12.96 MPa and 13.44 MPa respectively.

According to the single curve assumption, curve $\sigma_i - \varepsilon_i$ can be replaced by simple stretch curve $\sigma - \varepsilon$ [40]. Based on the direct tensile test results of mudstone and sandstone[41], the effective strain strengths of the overburden layer (7) and (8) in the damage zone of Zhang Huaizhu working face are estimated to be 6.5×10^{-6} and 8.5×10^{-6}, respectively.

4.2.5 Subsidence of unconsolidated layers

According to the engineering geological survey data of Zhangzhuang Coal Mine, unconsolidated layers on site are buried at a depth of $H=65\text{ m}$ and consist of clay and silty sand. Fig.13 shows that the unconsolidated layer strain monitored by the optical fiber sensor is greatly affected by the external temperature and looseness, and it is difficult to accurately reflect the deformation characteristics of the overlying rock and soil. Thus, it is unreliable to use the monitored strain to calculate subsidence of unconsolidated layers by Eq.(14). Assume that the subsidence of the soil in unconsolidated layers follows the law of elastic deformation in this field test, then the subsidence of unconsolidated layers can be calculated by:

$$W=\frac{\gamma H^2}{2E_s} \tag{25}$$

where E_s is compressive modulus of the soil. After calculation, the final subsidence value of the unconsolidated layers in this field test is 3.61 mm. Since the distributed optical fiber monitoring of Zhangzhuang Coal Mine was performed one and a half years later after mining, it can be assumed that the subsidence value of the unconsolidated layers in the monitoring period has reached the final value and remained unchanged.

4.3 Calculation results of overburden subsidence above the gob

Based on the strain data of the mined-out area measured on October 2, 2013, the Eq.(7), Eq.(13), and Eq.(14) are used to calculate the subsidence of each zone in Zhang Huaizhu working face with time, and Fig.14 shows calculation results.

As shown in Fig.14, the cumulative subsidence of ground surface was 7.72 mm. The subsidence of the bulking zone, damage zone and ground surface above the gob gradually increased with time and showed a relationship of negative exponential function. The total subsidence values of the bulking zone and damage zone were 1.21 mm and 2.46 mm, which accounted for 15.7% and 31.9% of the surface subsidence, respectively. Hence, the damage zone contributes more to ground subsidence than the bulking zone. After the coal seam was mined, the subsidence in the bulking zone was affected by the large gap between the rock mass particles, so during the monitoring period, the subsidence of the bulking zone gradually became faster and remained unstable. The damage zone was affected by the continuous development of cracks and stress redistribution, so during the monitoring period, the overburden subsidence tended to be stable. The subsidence of the continuous deformation zone gradually increased with time, and had the tendency to be stable. Because the proportion of the height of the continuous deformation zone is large (64.6% of the overburden height), the subsidence of this area is the main contribution zone to surface subsidence. According to the “Code for Coal Pillar Retention and Coal Mining in Buildings, Water Bodies, Railways and Main Shafts”[36], when the sinking value of the local surface point does not exceed 30mm for 6 consecutive months, the surface movement period is considered to be finished, so the ground surface subsidence of this coal mine reached a stable stage.

In order to verify the rationality of the overburden subsidence calculation model proposed in this paper, the calculation result of this model, the result of the sensor returned strain integral method and the monitoring result by the surface hydrostatic levelling line at site were compared, as shown in Fig.15.

According to Fig.15, the relative error between the result of the subsidence calculation model and the on-site monitoring result is smaller than it of the monitored strain integral method. When $t = 348\ d$, the relative error of the subsidence calculation model reaches a maximum value and does not exceed 8%. It shows that the method proposed in this paper is trustworthy, and the model can be used to calculate the overburden subsidence in the gob.

5. Discussion

Aiming at the issue that the existence of cracks and voids in the bulking zone affects the continuity of the rock mass, the subsidence calculation model proposed in this paper takes the uneven deformation of the overburden rock within λ range of each monitoring point into account, which improves the calculation accuracy of the overburden subsidence in the gob. At present, the minimum spatial resolution and sampling interval of BOTDR among distributed optical fiber testing instruments are 1m and 5cm[23,24], and the minimum spatial resolution and sampling interval of optical frequency-domain reflectometry (OFDR) are 1mm[42]. With the spatial resolution and sampling interval of the DOFS instrument keep decreasing, the parameter λ in Fig.3 will reduce. At that time, the strain of the rock mass between monitoring points is more accuracy, and the result of the proposed calculation model based on the overburden subsidence is closer to the actual subsidence on site.

The monitored strain integral method used to calculate the subsidence overburden is based on the following assumption: the deformation of the rock mass between two adjacent monitoring points is evenly, and the subsidence is obtained by integrating the strain data among the whole height of the overburden[15,18,43,44]. When the amount of rock deformation is small or it is in the stage of elastic deformation, this method can meet the requirements of subsidence calculation. However, as the existence of voids and fractures in the rock mass makes it difficult to meet the evenly requirements of mining overburden above the gob.

When calculating damage factor of the bulking zone and the damage zone, the confining pressures were estimated by $P_0=\eta\sum\gamma h_z$. If it is possible, it is better to use the on-site monitoring data instead of estimated one. However, since the strain monitored by the optical sensor in the bulking zone and damage zone of Zhangzhuang Coal Mine was always smaller than ε_0 , the errors of confining pressure and damage distribution parameters have little effect on the subsidence calculation results. Also, if calculated using the simplified formula, Eq.(23), the accuracy of confining pressure need not to be considered.

For unconsolidated layers, the final subsidence was calculated. Compared with the actual subsidence process, the calculation model result is larger. The values of particle contact parameters in the bulking zone also cause errors of the calculation results. However, because the distributed monitoring was performed one and a half years later after coal mining, the overall strain value was smaller and had less impact. When calculating the damage zone subsidence, in order to satisfy plastic total deformation theory, we need to assume that the rock mass loading obeys the single load process. Although there is little cyclic loading phenomenon in the subsidence process of overburden rock after mining, there is an unloading process during coal mining. Therefore, the total deformation theory has certain errors, which require further research and discussion in the future.

6 Conclusion

According to the deformation and failure characteristics of the overburden rock above the gob, the overburden can be divided into the bulking zone, damage zone and continuous deformation zone. Based on the characteristics of the broken rock mass in the bulking zone, the fractured rock mass in the damage zone and the intact rock and soil in the continuous deformation zone, a measured strain based model for calculating subsidence can be proposed. The proposed model considers the uneven deformation of the rock mass and can reflect the relationship between the mechanical parameters and the subsidence of the overburden. It is also suitable to calculate the overburden subsidence above the gob when monitored by distributed optical fiber sensor.

The influence of the damage distribution parameters and the particle contact parameters on the subsidence calculation results were analysed. When the strain measured by the optical fiber sensor is less than ε_0, the value errors of the damage distribution parameters ε_0 and m_0 have little effect on subsidence calculation results. The influence of contact surface angle error on the subsidence in the bulking zone has a maximum value of 0.016 times the bulking zone height, while the influence of friction coefficient on the subsidence has a maximum value of 0.046 times the bulking zone height. According to these parameter analysis, the calculation model of the bulking zone in the stable stage and the damage zone in the whole stage can be simplified.

The proposed subsidence calculation model of overburden in the gob was applied to Zhang Huaizhu working face in Zhangzhuang mining area, and the subsidence value of each zone was obtained. The settlement speed of the bulking zone increases with time, while the subsidence of the damage zone and continuous deformation zone has a negative exponential function relationship with time, and gradually increases and stabilizes. Comparing the result by the proposed subsidence calculation model with the field data, it is found that the relative error between the two does not exceed 8%, which is less than the relative error of the result by the monitored strain integral method. The comparison result indicates that the calculation model proposed is suitable for deformation of the mining overburden. The subsidence calculation result based on the deformation state parameters meets the calculation requirements of overburden subsidence in the gob on site.

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Figure captions and table headings

Fig.1 Diagram of mining overburden state and stratum zoning

Fig.2 Distributed monitoring scheme for overburden in mining area

Fig.3 Monitoring points of the optical fiber sensor

Fig.4 Schematic diagram of simplification of compressive deformation of the rock mass in the bulking zone

Fig.5 Stress-strain curve of sandstone under different confining pressures

Fig.6 Change rules of distribution parameters and peak strain under different confining pressures

Fig.7 Influences of ε_0 and m_0 on the strain ε_r^b in the bulking zone

Fig.8 Influences of ε_0 and m_0 on the strain ε_r^d in the damage zone

Fig.9 Curve of θ's influence on the calculated strain ε_r^b in the bulking zone

Fig.10 Curve of μ's influence on the strain ε_r^b in the bulking zone

Fig.11 Layout location of hydrostatic levelling line and optical fiber monitoring point

Fig.12 Lowering of the optical cable on-site

Fig.13 Vertical strain distribution

Fig.14 Results of subsidence calculation model based on the measured strain in different zones

Fig.15 Ground surface subsidence results based on calculation model, integral method and field monitoring

Table 1 Physical and mechanical properties of the strata in Zhangzhuang coal mine

Table 2 Main technical performance indicators of N8511 optical fiber strain analyser

Table 3 Damage parameters of overburden in the gob