Research Article

Analysis on Subsidence Law of Bedrock and Ultrathick Loose Layer Caused by Coal Mining

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In the process of coal mining, when the buried depth is large and the loose layer is thick, the ground subsidence tends to be abnormal, thus causing great damage to the surface ecological environment. In order to reveal the mechanism of mining ground subsidence under ultrathick loose layer, taking 1305 working face of a mine as the background, the law of mining ground subsidence under ultrathick loose layer was analyzed through field measurement. The law of bedrock subsidence is analyzed by similar simulation test, and the role of ultrathick loose layer in bedrock subsidence is quantitatively analyzed. The hydrophobic settlement model of ultrathick loose layer is established by settlement theory calculation, and the law of ground subsidence caused by hydrophobic of ultrathick loose layer is analyzed. The results show that the ground subsidence is mainly composed of bedrock subsidence and hydrophobic settlement of ultrathick loose layer. The maximum ground subsidence measured in the field is 4.201 m, the bedrock surface subsidence obtained by the simulation test of similar materials is 3.552 m, and the subsidence of ultrathick loose layer obtained by hydrophobic settlement analysis is 0.58 m. Adding the subsidence of bedrock surface and the subsidence of ultrathick loose layer, the ground subsidence is 4.132 m. It is in good agreement with the total ground subsidence measured in the field, which verifies the rationality that the ground subsidence mainly includes bedrock subsidence and hydrophobic settlement of ultrathick loose layer.

1. Introduction

After coal seam mining, the balanced stress state in surrounding rock was broken, and the overlying strata began to move from bottom to top. At last, there would be forming collapse zone, fissure zone, and bent subsidence zone in overlying strata from bottom to top [1]. When the bent subsidence zone extends to the ground, it will cause the ground to subsidence. The process of ground subsidence is always accompanied by water resources loss, which will inevitably cause damage of ecological environment. Therefore, in the process of coal mining, to minimize ground subsidence is a major aspect of protecting ecological environment [2, 3]. Above the coal seam, the overlying strata can be divided into two parts: bedrock and loose layer. Li pointed out that a loose layer with a thickness of more than 50 m is called thick loose

layer, and a loose layer with a thickness of more than 100 m is called ultrathick loose layer [4]. Under the condition that the thickness of loose layer is less than 50 m, the ground subsidence coefficient of coal seam mining (the ratio of maximum subsidence amount to coal seam thickness) is basically in the range of 0.7-0.8 [5]. When the loose layer is more than 50 m, the ground subsidence during coal seam mining is larger, and the corresponding ground subsidence coefficient is also larger. Once the loose layer exceeds 100 m, the ground subsidence coefficient is close to 1.0, or even greater than 1.0, which would bring great damage to the ecological environment [6].

After years of research, experts and scholars have established a variety of ground subsidence prediction models for coal seam mining, including prediction models based on mechanical properties of overlying strata, prediction models

based on the shape of ground subsidence basin, and prediction models to describe the dynamic subsidence process of a certain point. Many scholars contributed much to the first type of models. Singh [7, 8] established a ground subsidence prediction model based on the elastic-plastic theory and field observation data. Liu et al. [9, 10] combined the layered elastic plate controlling theory and stochastic medium theory to build the prediction model. Peng et al. [11] used structural mechanics to construct a prediction model. Yu et al. [12] established a prediction model of surface skew subsidence based on the key layer theory. For the second type of models, probabilistic integration prediction model and profile function prediction model are widely used [13]. The probabilistic integration method, also known as influence function method, is a prediction method developed by Liu et al. [14] based on stochastic medium theory. This method can be combined with artificial neural networks [15, 16], taking into account the weighting factors of parameters [17, 18] and the area of the goaf [19] to establish several modified probabilistic integral models. The section function method is a prediction method to approximately express the main section curve of the subsidence basin on the basis of the measured data and based on the empirical formula. Section functions include Exponential function [20–22], Gaussian function [23], Composite power function [24], and Boltzmann function [25]. The time parameter is indispensable in the dynamic prediction model of ground subsidence. The Knothe time function model is considered to be the basic model to describe the dynamic developing law of mining subsidence [26–28]. Widely used time function models include Normal distribution function model [29], Sroka-Schober two-parameter time function model [30], Gompertz time function model [31], Logistic time function model [32], Weibull time function model [33], Ichards time function model [34], and MMF model [35].

A large number of on-site engineering practices show that the movement of ultrathick loose layer is different from that of bedrock [36]. In view of the mining under ultrathick loose layer, Zuo et al. [37] pointed out that the bedrock shows an inverted funnel-like fracture, the loose layer emerges a funnel-like movement, and the overall movement of the overlying strata presents a “quasi-hyperbolic” shape. Zhou [38] indicated that under thick loose layer, the ground subsidence amount consists of four parts: loose layer subsidence caused by bedrock subsidence, subsidence due to synergistic action of bedrock and loose layer, the water loss consolidation subsidence of the loose layer, and the compactness subsidence of shallow loose layer under mining disturbance. Cui et al. [39] and Liang et al. [40] revealed that under thick loose layer, the subsidence caused by aquifer hydrophobic settlement is a vital part of ground subsidence in mining process.

Based on the above analysis, the existing prediction models of surface subsidence mainly predict the final settlement state of the ground, while the quantitative analysis of deformation laws of bedrock and loose layer in overburden is rarely studied. At the same time, it can be seen that in the study of mining ground subsidence under the ultrathick loose layer, experts and scholars pointed out that the hydrophobic settlement of loose layer is one of the main aspects

leading to ground subsidence. Therefore, on the basis of previous studies, this paper analyzes the deformation laws of bedrock and loose layer. In this paper, the 1305 working face of a coal mine is taken as the engineering background, and the law of ground subsidence under the ultrathick loose layer is studied through field measurement analysis, similar material simulation analysis, and theoretical analysis. In this study, the difference of ground subsidence with or without ultrathick loose layer was compared and analyzed, the role of ultrathick loose layer in bedrock subsidence was revealed, and the proportion of bedrock subsidence in ground subsidence under the action of ultrathick loose layer in a coal mine was quantitatively analyzed. The hydrophobic settlement model of layered soil considering bedrock settlement is established, and the calculation method of layered soil settlement considering seepage and soil self-weight stress change is obtained. The proportion of hydrophobic settlement of ultrathick loose layer in ground subsidence is quantitatively analyzed, which provides a basis for surface subsidence control.

2. Field Measurements on Ground Subsidence

The thickness of the loose layer overlying the 1305 working face of a mine is 700 m, which belongs to the coal seam covered by the ultrathick loose layer. By setting up a ground observation station in the mining area, the law of mining ground subsidence under ultrathick loose layer was measured and analyzed.

2.1. Layout of Measurement Lines. In 1305 working face, the strike length is 1823 m, and the dip length is 223.6 m, and the dip angle of coal seam is 4–18° (average 13°). The thickness of coal seam is 1.8–4.9 m (average 4.04 m). The inclined long wall fully mechanized top coal caving method is adopted, and the roof is managed by all caving method. The 1303 working face is laid in the left of 1305 working face and has been mined out. The 1307 working face is laid in the right of 1305 working face and has not yet been mined. In the 1303 working face, the strike length is 2070 m, and the dip length is 210 m, and the dip angle of coal seam is 5°. The thickness of coal seam is 2.99 m in average. In 1305 working face, the thickness of each rock stratum and some mechanical parameters of each rock stratum are shown in Table 1.

The 1305 working face has a strike observation line with a length of 4800 m, with 136 monitoring points (Z1–Z136 in sequence from the starting direction to the stop line direction) and a dip observation line with a length of 2800 m, with 60 monitoring points (H1–H60 in sequence from left to right), so 196 monitoring points are arranged within the 1305 working face (Figure 1). In the setting process of survey lines, on the one hand, it is influenced by the villages on the ground; on the other hand, it is convenient for monitoring, and some survey points in the two survey lines deviate from the main section.

There are 22 observation phases in the mining process of No. 1305 working face. The data of first phase is the reference data before coal seam exploited, and the data of 22nd phase is the settlement data after ground stability. Observation was

TABLE 1: Parameters of strata.

Strata	Thickness/m	Density/kg·m ⁻³	Uniaxial compressive strength/MPa	Tensile strength/MPa	Elasticity modulus/GPa	Cohesion/MPa	Internal friction angle/°	Poisson ratio
Loose layer	724.7	2210						
Fine sandstone	1.6	2340	76.8	6.9	19.6	19.28	36	0.26
Mudstone	75.09	2470	40.8	5.7	6.56	11.36	30	0.32
Fine sandstone	3.87	2340	76.8	6.9	19.6	19.28	36	0.26
Mudstone	5.98	2470	40.8	5.7	6.56	11.36	30	0.32
Fine sandstone	15.15	2340	76.8	6.9	19.6	19.28	36	0.26
Mudstone	8.15	2470	40.8	5.7	6.56	11.36	30	0.32
Fine sandstone	16.18	2340	76.8	6.9	19.6	19.28	36	0.26
Coal 3	4.04	1350	15.8	1.8	3.52	4.82	28	0.33
Mudstone	4.01	2470	40.8	5.7	6.56	11.36	30	0.32
Fine sandstone	10.7	2340	76.8	6.9	19.6	19.28	36	0.26

FIGURE 1: Layout of observation lines within the working face.

conducted once every 0.5-3 months. Due to the damage of measuring point markers, some data are missing, and the ground subsidence curve is interrupted.

2.2. Analysis of Measured Results. In strike, taking Z01 as the coordinate origin, from Z01 to Z136, the ground subsidence curve of 1305 working face is obtained, as shown in Figure 2. In the survey line, three measuring points Z71, Z58, and Z43 deviate from the strike principal axis, and the settlement values of these three measuring points are reduced due to the boundary effect, so the corresponding positions in the curve show uplift. In addition, there is a flat bottom in the middle of the curve, which indicates that 1305 working face

has achieved full mining. In curve of the last survey cycle, since the measuring points deviating from the principal axis are basically within the flat part of the curve, the settlement value of the points deviating from the strike principal axis can be replaced by the average settlement value of the flat part. After sinking, the maximum settlement value is 4.201 m. The average thickness of coal seam is 4.04 m, and the subsidence coefficient within the working face is 1.04 (the ratio of maximum settlement value to average thickness of coal seam). According to [41], the point with settlement value of 10 mm is the mining influenced boundary point. According to the curve of the last survey cycle, the mining influenced range is determined to be from 796 m behind the open-off cut to 786 m in front of the stop line. According to [41], when there is loose layer, along the moving angle of loose layer (usually 45°), the first line is drawn from the boundary of the self-moving basin to the bedrock. Then, the second line is drawn from the intersection point to the goaf boundary. The angle between the second line and the horizontal line on side of the coal pillar is the boundary angle (Figure 3). The thickness of loose layer in 1305 working face is about 724.7 m, and the thickness of bedrock is 126.25 m. Therefore, at the open-off cut side, the boundary angle of bedrock is calculated as 60.3° and that of stop line side is calculated as 63.8°.

In inclined survey line, from rise side to dip side, observation points are sequentially numbered H1-H60. There is an angle between the survey line and the inclined principal axis, which is perpendicular to the strike principal axis. Considering that the deformation such as the subsidence and horizontal movement of the measuring point mainly determined by the nearest mining activity, in data processing, the inclined principal axis is determined as the vertical line that through the intersection point of inclined survey line and the strike principal axis. The inclined principal axis is shown in Figure 1. The measuring points on the inclined survey line are projected to the inclined principal axis, and the settlement values of the observation points are used to express the settlement values of the corresponding projection points

FIGURE 2: Ground subsidence curves along strike principal axis of 1305 working face.

FIGURE 3: Schematic diagram of boundary angle determination.

on the principal axis. In inclined principal axis, the ground subsidence curve of 1305 working face is obtained as shown in Figure 4.

It can be seen that the closer to the inclined center, the greater the ground subsidence. The maximum subsidence at the inclined center of the working face is 4.163 m, and the average thickness of the coal seam is 4.04 m. The subsidence coefficient at this position is 1.03, which is basically consistent with the subsidence coefficient of the strike principal axis (1.04). Due to the short monitoring distance on the rise side and the small number of measuring points, the monitoring range cannot reach the mining influenced boundary. The monitoring distance on the dip side is long, and there are many measuring points. According to the curve of the last survey cycle, the monitoring range beyond the mining influenced boundary that was the point with 10 mm subsidence. In inclined principal axis, the mining influenced range is 822 m beyond the working face.

The subsidence data on the strike principal axis and the inclined principal axis of the last phase are used for three-dimensional fitting, and the ground subsidence basin is

obtained as shown in Figure 5. It is determined that the subsidence coefficient is 1.04. In strike, the boundary angles at the open-off cut side and stop line side are 60.3° and 63.8°, respectively. The monitoring distance on the rise side is short and does not reach the mining influenced boundary, while the dip side has a long monitoring distance, and the boundary angle is 53.9°.

3. The Law of Bedrock Movement under Ultrathick Loose Layer

This part mainly uses the method of physical material similarity simulation test to analyze the settlement law of bedrock. Meanwhile, the difference of bedrock settlement law of the model with and without superthick loose layer is compared and analyzed. The role of ultrathick loose layer in bedrock subsidence is quantified.

3.1. Design of the Similar Simulation Tests. Similar material tests were designed according to the geological conditions of 1305 working face. In 1305 working face, the buried depth

FIGURE 4: Ground subsidence curves along inclined principal axis of 1305 working face.

FIGURE 5: The ground subsidence basin in three-dimensional.

of coal seam is about 850 m, in which the thickness of loose layer is 724.7 m, the thickness of bedrock is 126.25 m, and the thickness of coal seam is 4.04 m. This test is carried out on experimental bench with sizes $3.0 \text{ m} \times 0.4 \text{ m} \times 3.0 \text{ m}$. Considering the thickness of coal seam and bedrock, referring to [42, 43], in testing, the geometric similarity ratio was designed as 1/100 (i.e., the ratio of size in test model to size in field is 1/100). According to similarity theory [42, 43], the bulk density similarity ratio (i.e., the ratio of bulk density in test model to bulk density in field) was 1/1.5, and the stress similarity ratio (i.e., the ratio of stress in test model to stress in field) was 1/150.

The similar model is mainly paved with sand, mica powder, sawdust, gypsum, cement, and other materials. According to the similarity ratio, different strata in the model are adjusted by the proportion of materials. In this part, two test models were designed. One model contained ultrathick loose layer, and the other model did not contain loose layer. According to the stratigraphic data paving model in Table 1, the rock parameters of the two models are the same. Because

some of the strata are thin, the thinner strata are merged with the adjacent strata in the model design. After the laying of the model, an external force is applied above one of the models to simulate the effect of the ultrathick loose layer. According to Table 1, the thickness of the ultrathick loose layer is 724.7 m, and the density of the loose layer is about 2210 kg/m^3 . The stress at the top of the bedrock (gravity density multiplied by buried depth) is calculated to be about 15.70 MPa. According to the stress similarity ratio of 1/150, the stress at the top of the model is calculated to be about 104.67 kPa, which is applied at the top of the model by the way of the hydraulic oil cylinder and I-steel. One of the paved models is shown in Figure 6.

After the model is laid, $10 \text{ cm} \times 10 \text{ cm}$ grid lines are laid on the front of the model with ink lines. The $2 \text{ cm} \times 2 \text{ cm}$ reflective sheets are inserted at the intersection of the grid, and the displacement of the reflector is accurately measured by an industrial measurement system. A total of 7 observation lines and 203 reflective sheets were designed in the upper part of coal seam. In models, from bottom to top, these lines

FIGURE 6: One of the paved models.

were named as A-15.5 line (i.e., 15.5 cm above the coal seam, and other lines were named similar to this), B-35.5 line, C-55.5 line, D-75.5 line, E-95.5 line, F-115.5 line, and G-125.5 line.

After the model is laid, the coal seam is excavated after drying for 15 days. In order to reduce the influence of boundary effect, 40 cm protective coal pillars are left on the side of the open-off cut and on the side of the mining stop line. The total length of the model is 300 cm. After removing the coal pillar, the mining length is 220 cm. Before coal seam mining, the displacement of all reflective plates is observed, and the observation results are used as the basis for the comparison of the subsequent observation data.

During the experiment, 10 cm was excavated every time. Set aside 2 hours at the end of each excavation to stabilize the movement of the overlying strata, and then collect data. The next cycle of excavation, stability of overlying rock movement, and data collection will be carried out at the end of data collection. In order to compare with the field monitoring results, the displacement data used in the subsequent analysis were converted according to the ratio of geometric similarity ratio (1/100).

3.2. Analysis of Bedrock Movement with Ultrathick Loose Layer. The overlying rock movement process is shown in Figure 7; the direct roof has not collapsed when the working face is pushed 40.0 m, which is due to the size effect, and the overlying rock movement can not reflect the real overlying rock movement in the initial advancing stage. When the working face advances 60.0 m, the direct roof of 1.5 m above the coal seam collapses; when it advances 80.0 m, a large separation occurs at the position of 26.5 m above the coal seam, and the basic roof bends and sinks, but no collapse occurs. When the working face advances 100.0 m, the position of the separated layer extends upward from 26.5 m to 46.5 m; the basic roof beam breaks on both sides of the goaf, and there is a small crack in the rock layer above the 46.5 m position, but there is no obvious bending and subsidence of the rock layer above the 46.5 m position. When the working face is advanced by 120.0 m, the caving zone is still at the position of 46.5 m above the coal seam, but the cantilever rock in the goaf is fractured, and a few cracks appear above the position. When the working face is advanced by 140.0 m,

the fracture zone extends upward to the top of the model, and the overlying strata bends and sinks obviously with the expansion of cracks.

At the end of the mining of the working face, the subsidence law of different positions above the coal seam is obtained as shown in Figure 8. When the working face advances 200.0 m, due to the load of the overlying loose layer, the rock layer at the top of the model collapses outward, resulting in the fall of some displacement measuring points. It can be seen that the bedrock subsidence gradually decreases with the increase of the distance from the coal seam. At the end of the experiment, the bedrock top subsidence is 3.552 m, the bedrock crack expansion angle on the open-off cut side is 65.2° , and the bedrock crack expansion angle on the stop line is 61.4° .

3.3. Analysis of Bedrock Movement without Ultrathick Loose Layer. The movement process of overburden is shown in Figure 9 when there is no ultrathick loose layer. At the end of the advance, the fracture extension angle of the side of the open-off cut is 70.3° and that of the side of the stop line is 63.8° . At the end of mining in the working face, the subsidence law of measuring lines in different positions above the coal seam is obtained as shown in Figure 9(c). When the working face advances 160.0 m, the rock movement extends to the top of the model. At the end of the experiment, the maximum subsidence at the top of the model is 3.100 m, and the corresponding ground subsidence coefficient is 0.767. However, in the model with ultrathick loose layer, the maximum subsidence at the top of the model is 3.552 m; it can be seen that the subsidence of the overlying 724.7 m thick loose layer at the top of the bedrock is 0.452 m.

4. Analysis of Hydrophobic Settlement with Ultrathick Loose Layer

The movement law of bedrock is analyzed through the similarity simulation test, and it is concluded that when the range of moving rock strata extends to the top of the model, the water in the ultrathick loose layer will gradually percolate to the bottom rock strata along the crack. With the continuous water seepage at the bottom, the groundwater level in the whole seepage area will decrease, and the decrease of the groundwater level will increase the dead weight stress of the soil and then cause the settlement of the loose soil layer. Meanwhile, the seepage of groundwater level will also cause the soil to increase the effective stress and then cause the soil settlement. It can be seen that in the process of overlying rock movement, the overlying ultrathick loose layer will not only cause bedrock settlement in the form of load, but also hydrophobic settlement will occur in the ultrathick loose layer itself. In order to analyze the mechanism of hydrophobic settlement of thick loose layer, this chapter establishes a hydrophobic settlement model of ultrathick loose layer on the basis of bedrock subsidence and analyzes the law of ground subsidence caused by drainage of ultrathick loose layer combined with the change of water level in the field.

In order to effectively evaluate the settlement of the loose layer caused by drainage, the drainage of the loose layer at the

FIGURE 7: The bedrock movement under ultrathick loose layer: (a) excavation of 40 cm; (b) excavation of 60 cm; (c) excavation of 80 cm; (d) excavation of 100 cm; (e) excavation of 120 cm; (f) excavation of 140 cm; (g) excavation of 200 cm; (h) excavation of 220 cm.

bottom of the site is regarded as a pumping process, so that an obvious decrease of water level will be formed in the drainage area, and a water level drop funnel curve will be formed around it [44, 45]. In addition, the seepage inside and outside the pit under the action of water head difference is regarded as a unidirectional seepage from top to bottom in the hydrophobic area, and considering the influence of initial accompanying subsidence caused by rock subsidence on hydrophobic settlement, the model is established as shown in Figure 10.

It is assumed that the groundwater recharge source of the whole site is abundant; there is no confined water layer, and the seepage process conforms to Darcy's law [46].

Assuming that the original water table height is H and the water level drop caused by water seepage at the bottom is ΔH , then the lowered water depth of the groundwater level afterwards can be expressed as h ($h = H - \Delta H$). If the radius of the whole seepage area is r , the radius of the seepage influence area is R , and the permeability coefficient of the soil layer is k . The average flow rate of the section is denoted by $V = k(dy/dx)$. As such, the water flow can be expressed as [47]

$$Q = \frac{\pi k(y^2 - h^2)}{\ln(x/r)}. \quad (1)$$

FIGURE 8: The sinking curve of the bedrock at different positions with ultrathick loose layer.

The curve of the water drop is [47]

$$y^2 = h^2 + (H^2 - h^2) \frac{\ln x/r}{\ln R/r}. \quad (2)$$

4.1. Analysis of Soil Layer Settlement Caused by Water Level Drop. Due to the decrease of the water level, the dead weight stress of the soil increases, leading to the increase of the effective stress of the soil. This further causes settlement of the soil [48]. Above the water level, the effective stress increment is

$$\Delta\sigma'_1 = (H - y)(\gamma - \gamma'), \quad (3)$$

where y is the y -coordinate value of any point in the calculation area, γ is the weight of the soil after the water level is lowered, and γ' is the floating weight of the soil before the water level is lowered. The effective stress increment of the soil below the water level line is

$$\Delta\sigma'_2 = (H - y_0)(\gamma - \gamma'), \quad (4)$$

where y_0 is the height of the water level change.

Therefore, the settlement of the soil layer caused by the decrease of water level is as follows:

$$s_d = \sum_{i=1}^n \frac{\Delta\sigma'_1 H_i}{2E_{si}} + \sum_{j=1}^m \frac{\Delta\sigma'_2 H_j}{E_{sj}}, \quad (5)$$

where H_i is the height of the i -th layer soil, E_{si} is the compressive modulus of the i -th layer soil, n is the number of layers above the water level reduction line, H_j is the height of the j -th layer soil, E_{sj} is the compressive modulus of the j -th layer soil, and m is the number of layers below the water level reduction line.

4.2. Analysis of Soil Layer Settlement Caused by Soil Seepage. Due to the seepage at the bottom of the soil, the existence of water head difference will cause seepage in the soil, thus

changing the effective stress of the soil and leading to settlement [49]. Assuming that only the vertical one-dimensional seepage in the seepage area is considered, there are N layers of soil in the site, and the head difference of seepage is equal to the height of the water level. The permeability coefficients of each soil layer are expressed as $k_1, k_2, k_3, \dots, k_N$, respectively. The thickness of each soil layer is denoted by $h_1, h_2, \dots, h_N$, respectively. The weight of each soil layer is referred to as $\gamma_1, \gamma_2, \dots, \gamma_N$, respectively. Let the original water level height be H and the lowered value be h , then the lowered water level difference can be calculated as $\Delta H (\Delta H = H - h)$. Due to the movement of the rock layer, the accompanying settlement occurs at the bottom of the soil layer, and its settlement is $\Delta h(x)$. Therefore, for the seepage area, the total water level drop is $\Delta H - \Delta h(x)$, and the total head difference of seepage is $h + \Delta h(x)$. Let the total head of the i -th layer be $L_i(y)$. Then, it can be obtained according to the seepage control equation

$$\frac{\partial^2 L_i}{\partial y_i^2} = 0. \quad (6)$$

The head distribution equation of the i -th layer can be expressed as

$$L_i(y) = a_i y + b_i, \quad (7)$$

where a_i and b_i are the undetermined coefficients.

The boundary condition for the first layer of soil is

$$y = -\Delta h, L_1(y_0) = 0, \quad y = h_1 - \Delta h, L_1(y_1) = L_1. \quad (8)$$

Likewise, the boundary condition for the i -th layer of soil is

$$y = y_{i-1}, L_i(y_{i-1}) = L_{i-1}, \quad y = y_i, L_i(y_i) = L_i. \quad (9)$$

Its continuous condition is

$$y = y_i, L_{i+1}(y_i) = L_i(y_i), \quad (10)$$

$$y = y_i, k_{i+1} \frac{\partial L_{i+1}(y)}{\partial y} = k_i \frac{\partial L_i(y)}{\partial y}. \quad (11)$$

Considering the head condition of the top layer of soil

$$y = y_l, L_l(y_l) = h + \Delta h(x), \quad (12)$$

where l is the number of layers affected by seepage.

We can obtain the head at any position through

$$L_i(y) = (h + \Delta h(x)) \left(\frac{y - y_i - \Delta h}{k_i} + \sum_{j=1}^i h_j/k_j \right) / \sum_{j=1}^l h_j/k_j \quad (y_{i-1} \leq y \leq y_i). \quad (13)$$

FIGURE 9: The movement of the overburden strata without ultrathick loose layer: (a) excavation of 160 cm; (b) excavation of 220 cm; (c) the sinking law of the measuring lines without ultrathick loose layer.

FIGURE 10: The hydrophobic settlement model of the ultrathick loose layer.

As such, the sinking of the i -th layer due to water seepage is

$$s_i = \frac{L_i - L_{i-1}}{h_i} \gamma_w \frac{h_i^2}{2E_s} = \gamma_w h_i \frac{L_i - L_{i-1}}{2E_s}, \quad (14)$$

where γ_w is the severity of water and E_s is the compressive modulus of soil.

Given the increase of self-heavy stress caused by the decrease of water level and the seepage of soil, the settlement of soil becomes

$$S = \sum_{i=1}^n \frac{\Delta \sigma'_i H_i}{2E_{si}} + \sum_{j=1}^m \frac{\Delta \sigma'_j H_j}{E_{sj}} + \sum_{k=1}^l \gamma_w h_k \frac{L_k - L_{k-1}}{2E_s}. \quad (15)$$

4.3. Analysis of the Hydrophobic Settlement in 1305 Working Face. The observation hole near the middle of 1305 working face is selected, and the observation data from the beginning of mining of 1305 working face to the stable ground subsidence are extracted. The buried depth of water level is 132.76 m at the beginning of mining and 138.77 m at the end of surface deformation monitoring. The cumulative change of water level is 6.01 m in the mining process of 1305 working face. According to the field conditions, the value of E_s is 60 MPa; combined with the Formula (15), the drainage settlement of the ultrathick loose layer in the mining process of 1305 working face is calculated to be 0.58 m.

5. Discussion

In the similar simulation test of bedrock movement with and without ultrathick loose layer, the advancing distance of bedrock movement extending to the top of the model is 140.0 m and 160.0 m, respectively. The reason for this phenomenon is that in the model with ultrathick loose layer, t ultrathick loose layer is applied to the bedrock surface in the form of load, resulting in the bedrock in the model with ultrathick loose layer larger bending and sinking under the same

propulsion step distance. Correspondingly, when the bedrock movement extends to the top of the model, the propulsion length of the model with ultrathick loose layer is smaller than that of the model without loose layer.

At the end of the advance, in the model with loose layer, the expansion angle of bedrock fracture at the side of the open-off cut is 65.2° and that at the side of the stopping line is 61.4° . In the model with no loose layer, the expansion angle of the fracture at the open-off cut is 70.3° and that at the stopping line side is 63.8° . It can be seen that in the model with no loose layer, the fracture expansion angle at the open-off cut is 5.1° larger and that at the stopping line side is 2.6° larger. The reason for this is that although the overlying loose layer is applied to the upper surface of the model in the form of uniform load, the maximum bending deflection of the overlying rock beam occurs in the strike center of the goaf, and the deflection of the rock beam decreases with the increase of the distance from the strike center of the goaf. When the deflection of the strike center of the goaf accumulates to a certain extent, it will lead to the fracture of the rock beam. The fracture range of the rock beam will be smaller than the bending and sinking range under the action of the gravity of the rock beam. The corresponding fracture expansion angle of the model with the ultrathick loose layer is slightly smaller than that of the model without the loose layer.

Under the same conditions of bedrock occurrence and without the influence of ultrathick loose layer, the ground subsidence coefficient is 0.767 through similar simulation test, while under the action of ultrathick loose layer, the bedrock subsidence coefficient increases to 0.846. It can be concluded that the settlement coefficient of bedrock is further increased due to the load action of the ultrathick loose layer, which is consistent with the actual situation.

6. Conclusions

In this paper, the law of ground subsidence in mining under ultrathick loose layer is studied by field measurement and similar simulation and theoretical analysis, and the main conclusions are as follows:

- (1) Through the field measurement of ground subsidence in 1305 working face of a coal mine, it is found that the subsidence coefficient is large under the action of thick loose layer, the corresponding subsidence amount is 4.201 m, and the subsidence coefficient is 1.04
- (2) According to the similar simulation test, the top subsidence of bedrock is 3.552 m under the action of ultrathick loose layer, and the ground subsidence is 4.201 m according to the field measurement, so the proportion of bedrock subsidence in the ground subsidence is 84.6%
- (3) The hydrophobic settlement model of layered soil considering bedrock settlement is established, and the calculation methods of layered soil settlement considering seepage and soil self-weight stress change are given, respectively. Combined with the dynamic

observation data of coal mine water level, it is determined that the subsidence caused by hydrophobic ultrathick loose layer in the mining process of No. 1305 working face is 0.58 m. Combined with the subsidence at the top of bedrock obtained from the simulation test of similar materials, it is determined that it is in good agreement with the ground subsidence of 4.201 m measured on site. Furthermore, it is concluded that the hydrophobic settlement of loose layer accounts for 15.4% of the total ground subsidence

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publishing of this paper.

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