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THE ANALYSIS OF SURFACE DEFORMATION CONTROLLED BY KEY STRATA GROUPS AND SEPARATION IN STRIP MINING

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Abstract: In this paper, the key stratum theory is introduced in view of the small surface deformation value of the mining of thick coal mines in Gucheng Coal Mine. The analysis of geological drilling data in Gucheng Goal Mine determines three key strata groups and one main key stratum for controlling the surface deformation of the stratum above the No. 3 coal according to the stiffness and strength condition of the stratum. The breaking distance of the main key stratum in this Mine is determined to be 302–373.7 m in terms of the elastic foundation beam theory and the surface measured basin data. In addition, a large-scale separation model of the main key stratum of the five strip mining face of this Mine is established, and the quantitative calculation formula of the limit spanning of rock beam is proposed and applied to. Finally, the probability integral method is used to predict the surface deformation problem of multiple working faces, and the partition prediction is performed according to the key stratum breaking distance to obtain prediction values of surface deformation consistent with the fracture of key stratum in the study area.

Keywords*: *key strata groups, separation, breaking distance, surface deformation, probability integration

1. INTRODUCTION

During the process of coal seam mining, the movement of the overlying rock mass will inevitably cause surface deformation, whose theoretical value will be different from the actual observation because of the complicated motion law of the overburden.

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To this end, the key stratum theory is introduced to analyse the deformation of the surface with a study of several rock layers that play a major role in the overlying strata. The strata that control the whole or part of rock mass activities in the mining rock mass are called key strata (Qian et al. 2003). Those strata are mainly identified by their deformation and fracture characteristics, that is, when the key strata are broken, the subsidence of all or part of the upper strata is in harmony with each other. The former is called the main key strata, and the latter is called the sub-key strata. If there are weaker strata in them, they will constitute composite key strata (Sun et al. 2011). Key stratum group refers to the existence of multiple composite key strata or main key strata and sub-key strata in the overburden rock mass of coal seam. During the process of mining from single coal pillar to multiple strips, key stratum groups from bottom to top play the function of controlling surface deformation respectively (Jiang et al. 2018; Xu et al. 2004).

In multi-face mining (especially strip mining), because there are one or more key strata or composite key strata in the overlying rock mass of mining coal seam, the main key strata (or sub-key strata) of overlying rock mass do not all fracture, or part of them fracture, which shows that the deformation of the upper surface of multi-face mining is quite different. The subsidence value above some working surfaces is larger, while the surface of them is not sinking. Therefore, the broken distance of coal seam mining face is calculated according to the theory of key strata, and the mechanical model of large-scale separation of key strata is established. And the analysis of the deformation of the surface is given through whether the key strata fracture or not to reveal the influence of the movement law of mining rock mass on the surface deformation. The surface movement probability integral method predicts that different expected areas should be divided according to the broken conditions of key strata. Because the parameters of surface movement in key strata are quite different from those in non-fracture strata, a partition prediction model should be established to reduce the surface deviation prediction bias. It is verified by partition prediction that the movement of key stratum groups and separation layers plays an important role in surface deformation, which is of great theoretical and practical significance to study the prediction and control of impact surface deformation in mining area.

2. THE JUDGMENT OF KEY STRATUM

2.1. THE JUDGMENT PRINCIPLES OF KEY STRATUM

2.1.1. STIFFNESS CONDITIONS

The location of hard strata in overburden strata is determined from bottom to top by the stiffness. Through the geological exploration data of the mining area, its overlying lithology is analysed to determine the location of the hard rock formation. The hard rock layer here is not that in the general sense, and it refers to those rock layers whose deflection is less than the lower rock layer in deformation without coordinating deformation with the lower rock layer. It is assumed that the first layer is hard rock, and that the upper to the *m*th stratum is compatible with the deformation, while the *m.* + 1-th stratum is not, the *m*+1th stratum is the second layer of hard rock (Wang et al. 2018; Ju et al. 2013; Xu et al. 2007).

Stiffness conditions:

$$q_1(x)\,|\,m+1 < q_1(x)\,|\,m\,, \tag{1}$$

where: $q_1(x)|m$ – the load of the mth layer on the formation of the first layer; $q_1(x)|m + 1$ – the load of the m + 1-th layer on the formation of the first layer.

$$q_1(x)\,|\,m = E_1 h_1^3 \sum_{i=1}^{m} \frac{h_i \gamma_i}{\sum_{i=1}^{m} E_i h_i^3}\,, \tag{2}$$

where: h_i, γ_i and E_i represent the thickness, bulk density, and elastic modulus of the i-th rock stratum, respectively (i = 1, 2, 3, ..., m).

The load formed by the m + 1-th layer on the first hard rock formation is:

$$q_1(x)\,|\,m+1 = E_1 h_1^3 \sum_{i=1}^{m} \frac{h_i \gamma_i}{\sum_{i=1}^{m+1} E_i h_i^3}\,. \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1) and simplifying it:

$$E_{m+1} h_{m+1}^2 \sum_{i=1}^{m} h_i \gamma_i > \gamma_{m+1} \sum_{i=1}^{m} E_i h_i^3\,. \tag{4}$$

Since the m + 1-th stratum is a hard rock stratum whose deflection is smaller than the that of the lower rock stratum, the rock stratum above the m + 1-th stratum no longer needs the lower rock stratum to bear the load it bears. Equation (4) is the formula for judging the position of the hard rock formation. For specific discrimination, calculate $E_{m+1} h_{m+1}^2 \sum_{i=1}^{m} h_i \gamma_i$ and $\gamma_{m+1} \sum_{i=1}^{m} E_i h_i^3$ layer by layer from the first layer above the coal seam. When the formula (4) is satisfied, it is no longer upward. In this case, the first stratum of rock formation goes up to the m + 1-th stratum of rock formation as the first hard rock stratum. Starting from the first hard rock formation, determine the location of the second hard rock formation as described above, and so on, until the uppermost hard rock formation (set as the nth hard rock stratum) is determined.

Through the discrimination of them, the location of the hard rock in the overburden and its controlled soft rock stratum are obtained.

2.1.2. STRENGTH CONDITIONS

The broken distance of each hard rock stratum is calculated and compared according to the strength condition to determine the position of the key stratum.

Strength condition:

$$l_m < l_{m+1}\ (k=1, 2, ..., n)\,, \tag{5}$$

where: l_m and l_{m+1} are the broken distances of the m, $m+1$ hard rock strata, respectively.

$$l_m = h_m\sqrt{\frac{2\sigma_m}{q_m}}\ (k=1, 2, ..., n)\,, \tag{6}$$

where: h_m is the thickness of the mth stratum hard rock, m; σ_m is the tensile strength of the m-th layer hard rock stratum, MPa; q_m is the load that the m-th layer hard rock stratum bears, MPa.

Thus we can see that

$$q_k = \frac{E_{k,0}h_k^3\sum_{i=1,k}^{m} h_{k,j}\gamma_{k,j}}{\sum_{j=1}^{m} E_{k,j}h_{k,j}^3}\ (k=1, 2, ..., n-1)\,, \tag{7}$$

where: the subscript k is the k-th hard rock formation; the subscript j is the layer number of the rock formation group controlled by the k-th hard rock formation; m is the number of layers of the soft rock stratum controlled by the k-th hard rock formation; $E_{k,j}$, $h_{k,j}$, $\gamma_{k,j}$ and are the elastic modulus, layer thickness and bulk density of the j-th layer in the soft rock stratum controlled by the k-th hard rock stratum, respectively, in units of GPA, m, and kN/m^3.

If the broken distance of the k-th hard rock stratum is greater than that of the $k+1$-th hard rock stratum above, the load of the latter is added to the former, and the broken distance of the k-th hard rock stratum is recalculated. If the recalculated kth hard rock stratum is less than that of the $k+1$-th hard rock, then take $l_k = l_{k+1}$. It is indicated that the fracture of the k-th hard rock stratum is controlled by the $k+1$-th hard rock stratum, that is, the k-th hard rock stratum is not broken before the break of the $k+1$ hard rock stratum. Once the hard rock stratum in layer $k+1$-th fractures, its load acts on the hard rock in layer k, causing the k-th layer hard rock to break.

2.2. CLASSIFICATION OF KEY STRATUM

The monitoring data from the surface deformation observation stations set up at each mining face of No. 3 coal mine in Gucheng Coal Mine show that the surface subsidence value of one mining face is different from that of two mining faces, three mining faces and many mining faces. When the number of faces is up to 5, the deformation value of the surface dose not grow any more with the increase of the mining faces, and the maximum deformation value of the surface is stable to a fixed value.

Lithology	Thickness(m)	Depth(m)
Quaternary	180.15	180.15
Fine sandstone	68.23	248.38
Sandy mudstone	30	278.38
Fine sandstone	180.97	459.35
Sandy mudstone	56	515.35
Fine sandstone	290.97	806.32
Sandy mudstone	78	884.32
Fine sandstone	208.88	1093.2
Red mudstone	60	1153.2
Fine sandstone	35.98	1189.18
Sandy mudstone	15	1204.18
Sandstone	53.3	1257.48
2 coal	0.94	1258.42
Sandstone	27.4	1285.82
3 coal	8.76	1294.58
Sandstone	44	1338.58
Sandy mudstone	10	1348.58
6 coal	0.72	1349.3

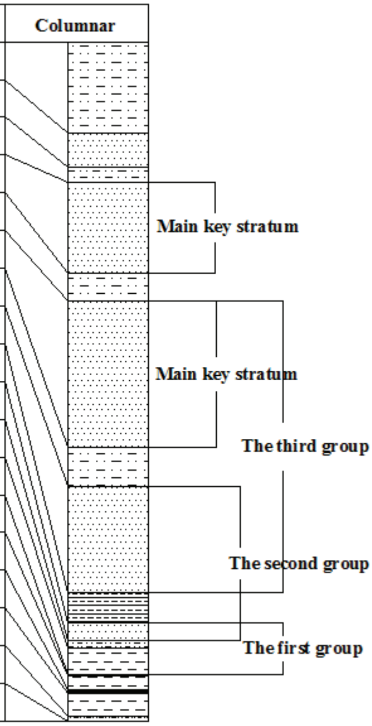

Fig. 1. Column diagram of No. 3 coal in Gucheng Coal Mine

According to the column diagram 1 of Gucheng Coal Mine No. 21 mining area, there are many layers of the overlying hard rock in this area, and the properties of rock are very similar. The direct roof of No. 3 coal in Gucheng Coal Mines and stone is sandstone with a thickness of 27.4 m, above which is No. 2 coal with a thickness of 0.94 m. It is preliminarily determined that there are three main and sub-key strata groups from No. 3 coal up, and they intersect with each other. For example, the main key stratum of a group is the sub-key stratum of another one. It can be ascertained that the composite key strata consisting of the second and third strata of hard rock and their weak intercalary strata play a major role in the surface movement and deformation of mining area, and that the fine sandstone with a thickness of 290.97 m and a distance of 479.5 m from No. 3 coal plays a major role in controlling the surface movement in multi-strip mining.

2.3. MOVING CHARACTERISTICS OF COMPOSITE KEY STRATA

When the strength of the two hard rock layers is the same, the relationship between the key stratum fracture and its thickness is as follows (Liao et al. 2005).

- When $h_2/h1 \leq 1.6$ (h_1 is the sub-key stratum of the key stratum group, and h_2 is the main key stratum of the key stratum group), the upper hard rock stratum will not fall along with the lower hard rock stratum, then the former is the main key stratum, and the latter is the sub-key stratum.
- When $h_2/h_1 = 1.6$, the upper hard rock stratum will fall along with the lower hard rock stratum, then the lower hard rock stratum becomes the only key stratum in the overburden. This is due to the change of the thickness of the upper hard rock stratum, which has an effect on the stress distribution of the lower hard rock stratum.
- When $h_2/h_1 > 1.6$, h_1 and h_2 can be regarded as composite key strata, which can better reflect the controlling effect of key strata in rock stratum activities.

According to the above relationship, the movement characteristics of each group of key strata is judged by calculation.

- The first key stratum group.
- Sandstone: h_1=53.3 m, Sandy mudstone: $\Sigma h_2 = 15$ m (Σh_2 is a medium-soft rock stratum in key strata), Fine sandstone: $h_2 = 35.98$ m, $h_2/h_1 = 35.98/53.3 < 1.6$. It shows that the upper part h_2 is the main key stratum, the lower part h_1 is the sub-key stratum, and the former does not fall synchronously with the latter.
- The second key stratum group.
- Fine sandstone: $h_1 = 35.98$ m, Red mudstone: $\Sigma h_2 = 60$ m, Fine sandstone: $h_2 = 208.88$ m. $h_2/h_1 = 208.88/35.98 > 1.6$. It reveals that the upper part h_2 and the lower part h_1 are composite key strata.
- The third key stratum group.
- Fine sandstone: $h_1 = 208.88$ m, Sandy mudstone: $\Sigma h_2 = 78$ m, Fine sandstone: $h_2 = 290.97$ m. $h_2/h_1 = 290.97/208.88 < 1.6$. It indicates that the upper part h_2 is the main key stratum, the lower part h_1 is the sub-key stratum, and the former does not fall synchronously with the latter.
- Main key stratum.
- The 290.97 m thick fine sandstone with 479.5 m away from No. 3 coal is the key stratum.

3. KEY STRATUM BREAKING DISTANCE CALCULATION

3.1. CALCULATION OF KEY STRATUM BREAKING DISTANCE ACCORDING TO ELASTIC FOUNDATION BEAM THEORY

According to the drilling histogram and measured mechanical parameters of the working face, in addition to the composite key stratum, the 290.97 m thick fine sandstone with a distance of 488 m from No. 3 coal is the main key stratum in the working face. The analysis combined with the coal seam strip mining underground working surface layout can confirm that the key stratum of 290.97 m thick sandstone is the beam on the elastic foundation which conforms to the Winkler hypothesis. Then the initial breaking distance of the fine sandstone rock layer is the breaking distance of the elastic foundation beam. The mechanical parameters of the overlying rock above the mining coal seam are shown in Table 1.

Table 1. Synthesis of rock physical and mechanical properties

	Red mudstone	Sandy mudstone	Fine sandstone	Sandstone
Bulk density [Kg/m^3]	2.54	2.56	2.60	2.56
Compressive strength [MPa]	12.98	28.08	29.84	63.27
Elastic Modulus [GPA]	0.61	0.97	1.02	2.73
Poisson's ratio	0.28	0.23	0.23	0.19
Cohesive force	3.59	4.86	5.01	7.81
Internal friction angle [°]	34.04	35.52	38.80	38.97
Tensile strength [MPa]	1.02	1.46	1.51	2.48

Due to the symmetry of the beam, the mechanical analysis of the half length of the beam is conducted before the initial fracture of the beam. According to the balance principle of the beam (Li et al. 2015; Huang et al. 2009), the deflection curve equation of the beam is

$$EI\,y^{(4)} = q(-1 \le x \le 0)\,, \tag{8}$$

$$EI\,y^{(4)} = q - ky(0 \le x \le \infty)\,. \tag{9}$$

Substituting boundary conditions and continuous conditions, the initial breaking distance l of the elastic foundation beam is as shown in formula (9).

$$10\sqrt{2}\omega^2 ql^3 + 60\omega ql^2 + (60\sqrt{2}q - \sqrt{2}h^2\sigma_c\omega^2)l - 2h^2\sigma_c\omega = 0\,, \tag{10}$$

where: $\omega = \sqrt[4]{\frac{k}{EI}}$, k is the Winkler elastic foundation coefficient, and $k = \left(\frac{E_0}{d_0}\right)^{\frac{1}{2}}$; E_0 is the elastic modulus of the foundation, MPa; d_0 is the thickness of the elastic foundation under the beam, m; E is the elastic mode of the fine sandstone formation, MPa; I is the moment of inertia of the cross-sectional area of the beam to the neutral axis; q is the load of beam itself and its upper rock, MPa; h is the thickness of the fine sandstone formation, m; σ_c is the ultimate compressive strength of the fine sandstone formation, MPa.

Substituting the relevant parameters into Eq. (9), the initial breaking distance of the 290.97 m thick fine sandstone rock formation on the elastic foundation is 373.7 m.

3.2. A METHOD FOR CALCULATING THE MAIN KEY STRATUM SUSPENSION WIDTH ACCORDING TO THE SURFACE MEASURED SUBSIDENCE BASIN

With the excavation of the mining face, the suspended ceiling area of goaf is continuously expanding. When excavating to a certain distance, the direct roof gradually collapses, the main roof gradually fractures, and the upper rock stratum begins to bend and sink (Xu et al. 2005). As the mining face continues to advance, the main roof has gradually collapsed. Owing to the vertical distance of 488 m between 290.97 m thick sandstone as the main key stratum and the goaf, the mining surface of multiple strips can affect the main key stratum leading to the separation of the main key stratum and its lower rock stratum which results in a suspension and forms a rectangular plate-like structure with four sides fixed and bearing the overburden load, as shown in Fig. 2.

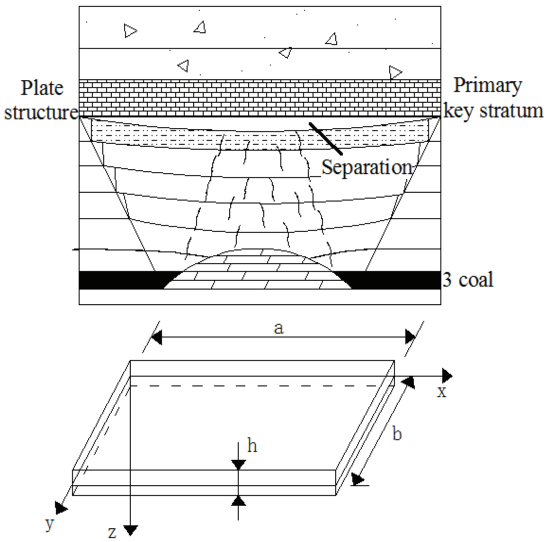

Fig. 2. Schematic diagram of the plate structure

When the suspension area continues to expand, the tensile strength of the rock mass is much smaller than its shear and compressive strength, causing the extensional fractures of the plate-like structure. The literature (Xu et al. 2018) shows that the stress at the midpoint of the long edge of the upper surface edge of the plate-like structure reaches the tensile strength limit of the rock mass and begins to break.

According to the characteristics of the surface subsidence basin, along the trend of the profile, the schematic diagram of the movement of the rock formation is shown in Fig. 3.

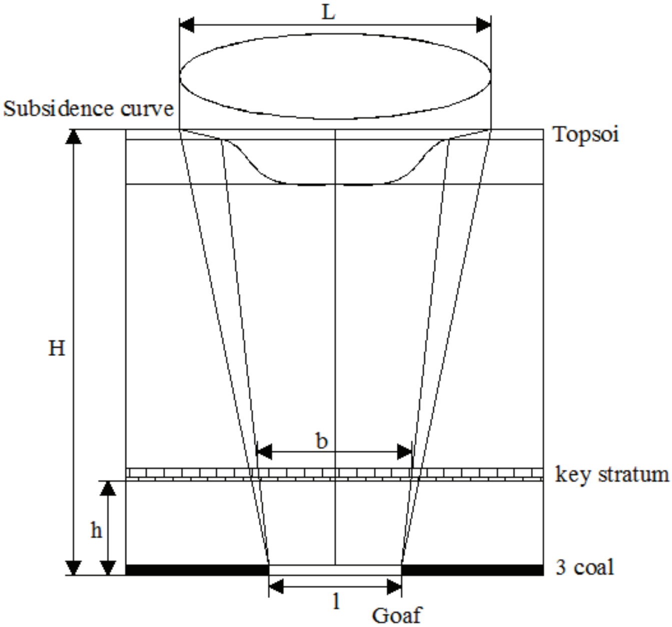

Fig. 3. Schematic diagram of rock movement

Using the mutual geometric relationship between the boundary angle and the movement angle of the rock formation, the main key stratum suspension width b' is approximated:

$$\frac{b'-l}{L-l}=\frac{h}{H}, \tag{11}$$

where: L is the diameter of the surface subsidence basin, m; l is the width of the goaf, m; H is the depth of the place, m; h is the distance between the main key stratum and the No. 3 coal seams, m.

According to the relationship between field measurement and overburden horizon, $L = 710$ m, $L = 200$ m, $H = 1000$ m, $h = 200$ m, and $b' = 302$ m.

3.3. DETERMINATION OF KEY STRATUM BREAKING DISTANCE

The broken distance of the key stratum of the No. 3 coal mining in Gucheng Coal Mine is 373.7 m, based on the theory of elastic foundation beam. According to the surface measured subsidence basin, the main key stratum has a suspension width of 302 m. Combining the aforementioned two methods, the broken distance of the key stratum of the No. 3 coal mining in Gucheng Coal Mine is determined to be 302~373.7 m.

3.4. ANALYSIS OF KEY STRATUM BREAKING

The 2103 working face is extremely inadequate mining due to the considerable depth of mining. the amount of surface subsidence after mining and the speed of surface subsidence during mining are small, and the subsidence velocity of surface points in the whole mining process does not exceed 1 mm/d at most. When the 2103 and 2105 working faces are mined, the surface subsidence velocity increases, and the surface subsidence basin expands, but the maximum surface subsidence is 15% higher than that of the single mining 2103 working face. After the mining of 2103, 2105 and 2106 working faces, the maximum surface subsidence values are basically the same as those

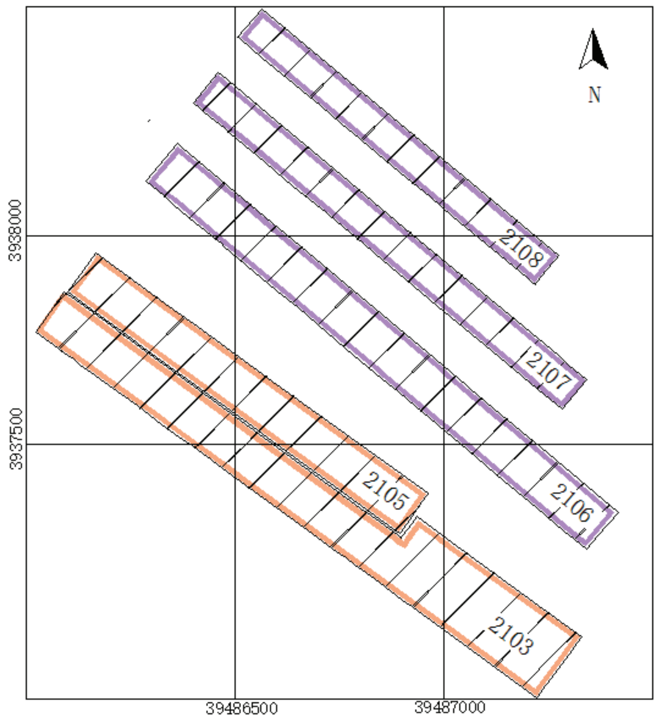

Fig. 4. Layout of working faces

after mining at 2103, 2105, 2106, 2107 and 2108 working faces. The layout of mining face is shown in Fig. 4. This situation indicates that the first or second composite key stratum above the coal seam has been fractured after the 2103 face is mined, and the main key stratum has been not broken. After the mining of 2103, 2105, 2106 working faces and subsequent 2103, 2105, 2106, 2107, 2108 mining faces, the first or second composite key stratum has been fractured; the main key stratum does not occur fracture. Increased subsidence shows that the main key stratum has moved, that is, there is a separation layer below the main key stratum.

Through analysis, it can be determined that the reasons for the lower subsidence values of the five working faces of Gucheng Coal Mine 2103, 2105, 2106, 2107, 2108 are that the overlying main key rock stratum is strong and not completely destroyed.

The existence of the main key stratum plays a certain supporting role for the overlying strata in the goaf, and continues to bear the overburden load to control the movement and deformation of the overlying strata and the surface.

4. DISCRIMINATION OF LARGE-SCALE SEPARATION OF KEY STRATA

4.1. ESTABLISHMENT OF A LARGE-SCALE SEPARATION MECHANICS MODEL OF KEY STRATA

After the deep strip working face is produced, the strip coal pillar generates compression deformation under the combined action of the self-weight stress of the overlying strata and the shifted stress in the goaf, and a large-scale separation mechanics model of high-level key stratum in deep well strip mining is established, as is shown in Fig. 5. The

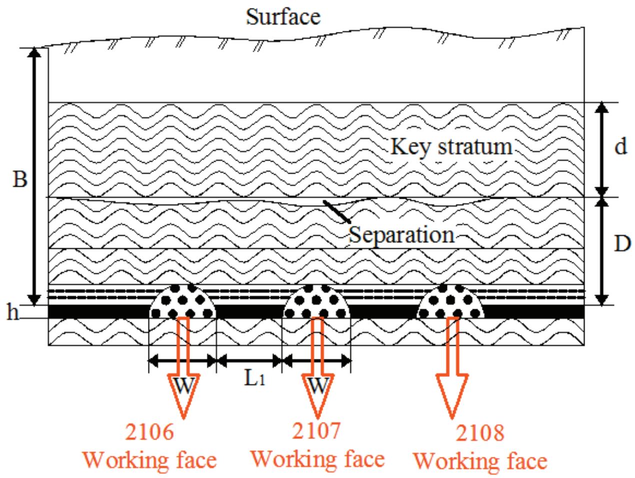

Fig. 5. Key stratum large-scale separation mechanics model

buried depth of the coal seam is B, the thickness of the key stratum is d, the distance from the coal seam to the key stratum is D, the width of the strip coal pillar is L_1 and the width of the strip working face is W.

The stress on the key stratum is simplified to a uniform load, and the key stratum is simplified to a fixed beam model at both ends. Load $q = \gamma(B - D)$ is on the key stratum. According to the elastic mechanics of the fixed beam at both ends under uniform load, the position where the key stratum is first damaged is located below the centre, which is tensile failure (Yu et al. 2015; B. et al. 2015; Ning et al. 2017).

The calculation formula for compression of strip coal pillars after mining is obtained as follows.

$$\nabla V = \varepsilon_0 h = \frac{(\sigma - \sigma_0)h}{E}, \tag{12}$$

where: ∇V is the compression of the strip coal pillar, m; ε_0 is the vertical compressive strain of the strip coal pillar; σ is the bearing pressure on the coal pillar after mining; σ_0 is the stress on the rock before mining. E is the elastic modulus of the coal seam, MPa.

According to the uniaxial tensile strength of rock beam, the ultimate span is

$$[l] = d\sqrt{\frac{[\sigma]}{q} + 1 + \frac{5}{4}\mu}, \tag{13}$$

where: $[l]$ is the ultimate span of the rock beam, m; d is the thickness of the rock beam; $[\sigma]$ is the uniaxial tensile strength of the rock beam, MPa; μ is the Poisson's ratio.

According to elasticity, the deflection of the axes of the fixed beam at both ends is

$$V = \frac{q}{(2E_1 d^3)}(x^3 - l^2), \tag{14}$$

where E_1 is the elastic modulus of the key stratum, l is the span of the rock beam, m; d is the thickness of the rock beam; γ is the average bulk density of the overlying strata, kN/m^3.

4.2. JUDGMENT OF LARGE-SCALE SEPARATION

The large-scale formation of the high-level key stratum in the strip mining depends on the limit span of the critical stratum and the compression of the strip coal pillars below it. When the stress, critical stratum limit span and critical stratum deflection conditions are satisfied at the same time, the high-level key stratum of the strip mining will have a large-scale separation layer in the lower rock stratum. The size of separation layer range is positively correlated with the critical stratum limit span, while negatively correlated with the critical stratum deflection.

The quantitative calculation formula is as follows (Jiang et al. 2018).

- When $L_1 < [l] \leq 2L_1 + W$, there will be no large-scale separation across the coal pillar.
- When $2L_1 + W < [l] \leq 3L_1 + 2W$, $l = 2L_1 + W$, $x = 0$, the deflection of the key layer rock beam at the coal pillar is $v_{x=0} = \frac{q}{2Ed^3} \cdot (2L_1 + W)^4$. If $v_{x=0} < \nabla V$, the separation layer can be formed across two goafs.
- When $3L_1 + 2W < [l] \leq 4L_1 + 3W$, $l = 3L_1 + 2W$, $x = L_1/2$, the deflection of the rock beam at the coal pillar is $v_{x=\frac{L_1}{2}} < \nabla V$, then the separation layer can be formed across three goafs.
- When $nL_1 + (n-1)W[l] \leq (n+1)L_1 + nW$, $n = 2i$, $i \in N$, $l = nL_1 + (n-1)W$, $x = 0$, the deflection of the rock beam at the coal pillar is $v_{x=0} = \frac{q}{2Ed^3}[nL_1 + (n-1)W]^4$, and if $v_{x=0} < \nabla V$, the separation layer can be formed across n goafs.
- When $L_1 + (n-1)W[l] \leq (n+1)L_1 + nW$ ($n = 2i$, $i \in N$), $l = nL_1 + (n-1)W$, $x = L_1/2$, the deflection of the rock beam at the coal pillar is $v_{x=\frac{L_1}{2}} = \frac{q}{2Ed^3}$ $\left\{\frac{1}{4}L_1^2 - [nL_1 + (n-1)W]^2\right\}^2$, and if $v_{x=\frac{L_1}{2}} < \nabla V$, the separation layer across n goafs can be formed.

4.3. ANALYSIS OF KEY STRATUM AND SEPARATION LAYER IN GUCHENG COAL MINE

The average mining depth of the 21 mining area of Gucheng Coal Mine is 1285 m; the thickness of coal seam is 8.6 m; the uniaxial resistance of coal is 26.17 MPa, and the elastic modulus is 6.72 GPA. The average density of the overlying strata is 25 kN/m^3. The strip mining method is adopted. The width of strip working face and strip coal pillar is 100 m and 120 m respectively. There are fine sandstones with a thickness of 290.97 m above No. 3 coal in mining area 21.

The fine sandstone with a thickness of 290.97 m in the stratum is the high key layer in the mining area; the elastic modulus E_1 is 60GPA; the tensile strength $[\sigma]$ is 12.5 MPa, and the Poisson's ratio μ is 0.22.

According to the stress condition of the separation of strip coal pillar, the distance between the key stratum and the coal seam is calculated as $D \geq 662.54$ m, and the distance from the coal seam to the key stratum is 770.47 m, which satisfies the stress condition of the separation layer. According to formula (13), the limit span of the key stratum is 373.7 m with the value between 360 m and 600 m, and the pressure relief width on both sides of the strip coal pillar is 20 m, so the effective load width of the coal pillar is 100 m. The compression of the coal pillar below the key stratum is 0.13 m, taking $l = 2L_1 + W = 360$ m, $x = 0$ based on formula (14), and the deflection of the key stratum at the coal pillar is 0.08 m. It can be seen that when $v_{x=0} < \nabla V$, the key stratum can form a large-scale separation layer with a span of 300 m.

It can be seen from the above calculation that when the stress condition for the occurrence of separation layer is satisfied, a separation zone will be generated below the key stratum. The thickness of No. 3 coal in Gucheng Coal Mine is 8.6 m, the maximum deformation value of the surface, however, is only 1.3 m, which is due to the formation of a separation zone between the 290.97 m-thick fine sandstone and the 78 m-thick sandy mudstone. This separation zone prevents the deformation inside the rock mass from propagating upward. As the mining progresses, the deformation below the key stratum does not propagate to the surface, which confirms the theory that the key stratum is capable of playing a role in controlling surface deformation. The calculation demonstrates that the limit span of the key stratum is 373.7 m. The 2106, 2107 and 2108 working faces are involved in this study. When the mining of 2107 working face is completed, the width of the goaf reaches 360 m, close to the limit span of the key stratum. With the mining of 2108 working face, the width of the goaf is bound to exceed the limit span, which may lead to the fracture of the key stratum.

5. DRILLING ANALYSIS OF SEPARATION ZONE OF OVERLYING ROCK MASS ON WORKING FACE

After large area strip mining, surface subsidence of 8.6 m-thick coal seam is only 1.3 m in mining area 21. To find out the cause of this, Gucheng Coal Mine constructed a borehole on the surface above 2103, 2105, 2106, 2107 and 2108 working goaf in June 2007 to detect the development height, development status (including space form of separation layer) and specific layer of overlying strata and fissure zone in working goaf 21, which reveals the cause of the such small surface subsidence.

Separation zones (248.38–278.38 m, 510.95–519.35 m) occur at the boundary between sandstone and mudstone, and develop in the mudstone at the bottom. Meanwhile, there will also be separation near the weak surface of huge thick rock, such as the separation zone 881.32–885.32 m, that is, the separation zone appears in the huge thick sandstone. Water leakage occurred in the drilling operation just after this section was exposed, which also proved the existence of the separation zone.

Performed after the final hole, ultrasonic imaging logging provided the data that reflected the spatial distribution of the separation zone better. Ultrasonic imaging logging interprets the distribution of separation zones as 258.38–280.38 (22) m, 510.95–519.35 (8.4) m and 881.32–885.32 (4.00) m. The separation height is 2.1–6.3 m with

19.35 (8.4) m and 881.32–885.32 (4.00) m. The separation height is 2.1–6.3 m with average height 4.2 m.

Development of drilling 510 m to 519 m separation layer is as shown in Fig. 6.

Drilling indicates that multiple separation spaces in the overlying strata in the mining area 21 of Gucheng Coal Mine become surface deformation equivalents, resulting in a small surface subsidence.

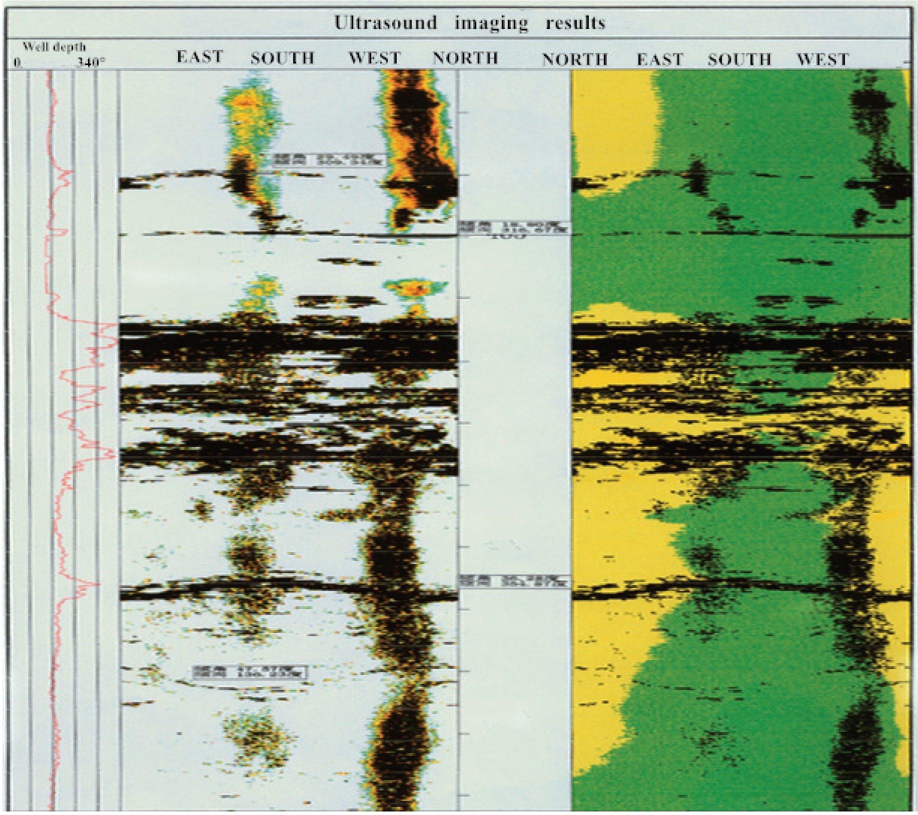

Fig. 6. Ultrasound imaging results

6. SUBAREA PREDICTION OF SURFACE DEFORMATION

The traditional probability integration method does not consider the impact of mining geological conditions on surface deformation. According to the movement and fracture of the key strata in different regions, the corresponding parameters are given to make an accurate and reasonable prediction of the surface subsidence, which has been improved in the article.

6.1. PREDICTION MODEL

The probability integral method takes the normal distribution function as the influence function and uses the integral formula to represent the surface subsidence basin section. The calculation is superimposed on the basis of the main section. The formula of calculating surface movement and deformation on the main section is as follows (Yao et al. 2012; Hao et al. 2006):

$$W(x) = \frac{W_{cm}}{\sqrt{\pi}} \int_{-\sqrt{\pi}\frac{x}{r}}^{\infty} e - \pi \left(\frac{x}{r}\right)^2 d\lambda \tag{15}$$

$$i(x) = \frac{W_{cm}}{r} e^{-\pi\left(\frac{x}{r}\right)^2} \tag{16}$$

$$K(x) = -\frac{2\pi W_{cm}}{r^2 \left(\frac{x}{r}\right) e^{-\pi\left(\frac{x}{r}\right)^2}} \tag{17}$$

$$U(x) = bW_{cm}e^{-\pi} \tag{18}$$

$$\varepsilon(x) = -2\pi b \frac{W_{cm}}{r\left(\frac{x}{r}\right) e^{-\pi\left(\frac{x}{r}\right)^2}} \tag{19}$$

Where, W, i, K, U and ε represent subsidence, tilt, curvature, horizontal movement and horizontal deformation respectively; W_{cm} represents the maximum sinking value of the surface; r represents the main influence radius of surface subsidence; b represents the horizontal movement coefficient; x represents the coordinates of the calculation point. With the offset of the inflection point taken into consideration, the origin of the coordinate is the projection of the calculation boundary on the surface. The direction of the coordinate axis pointing to the goaf is positive, and the direction pointing to the coal pillar is negative.

The movement deformation value of any point and any direction on the surface can be calculated by computer software.

6.2. DETERMINATION OF SURFACE ROCK DISPLACEMENT PARAMETERS FOR PARTITION PREDICTION

The surface deformation is predicted according to the parameters selected by the simulation prediction model for all the key stratum. The simulated sinking value from 28 to 43 is too different from the actual measured value, indicating that there are not all the fracture areas in the key stratum. Consequently, the selected parameters are inconsistent with the actual situation, the prediction model should be modified, and the probability integral method partition prediction model should be established.

In multi-face mining, the surface deformation is large in the key stratum fault area, while in the key stratum non-fracture area, the surface is basically not deformed. Both continuous mining of multiple working faces and strip mining have verified this rule. Because in the mining area with the key stratum controlling the surface deformation, the prediction error of the surface deformation according to the conventional probability integration method is too large. Thus, an improved probability integral method partition prediction model should be established.

According to the actual occurrence of the vertical fracture of the working face of the underground mining strip, the five working faces 2103, 2105, 2106, 2107 and 2108 are divided into the southern area and the northern area, and the three working areas of the south area 2103, 2105 and 2106 belong to the southern area. Assuming the key stratum faults, the calculation parameters of mining strata movement are determined as is shown in Table 2.

Table 2. Surface movement deformation parameters

Number of corner points	5	Coal seam dip angle (°)	0
Coal seam thickness (mm)	8000	Sinking coefficient	0.22
Main influence angle tangent	2.2	Mining influence propagation angle (°)	90
Working face maximum depth (m)	1295	Horizontal movement coefficient	0.25
Cutting step distance (m)	10	Inflection point displacement	0

The two working faces 2107 and 2108 in the north area belong to the southern area. Assuming that the key stratum is not broken, the calculation parameters for determining the movement of the mining face in the working face are shown in Table 3.

Table 3. Partition prediction parameters

Number of corner points	5	Coal seam dip angle (°)	0
Coal seam thickness (mm)	8000	Sinking coefficient	0.05
Main influence angle tangent	2.2	Mining influence propagation angle (°)	90
Working face maximum depth (m)	1295	Horizontal movement coefficient	0.25
Cutting step distance (m)	10	inflection point displacement	0

6.3. PARTITION PREDICTION OF SURFACE DEFORMATION

The regional prediction rock movement parameters are imported into the subsidence prediction software, and the surface deformation values of the mining area is obtained as shown in Table 4.

Table 4. Maximum surfer deformation after mining

	Maximum subsidence value (m)	Strike direction displacement value (m)	Inclination direction displacement value (m)
Deformation value	1.5032	+0.375 –0.381	+0.384 –0.379

6.4. PRECISION ANALYSIS

Through the overall prediction and considering the prediction of the key stratum without fracture, the measured value and the predicted value of the 28–44 point of the line is compared and analyzed in Table 5.

Table 5. Precision analysis

Error interval (mm)	Overall prediction		Partition prediction	
	Quantity	Proportion (%)	Quantity	Proportion (%)
$0 \leq \mid\Delta\mid \leq 50$	0	0	7	0.412
$50 \leq \mid\Delta\mid \leq 100$	1	0.059	2	0.118
$100 \leq \mid\Delta\mid \leq 150$	0	0	1	0.059
$150 \leq \mid\Delta\mid \leq 200$	2	0.118	1	0.059
$200 \leq \mid\Delta\mid \leq 250$	0	0	2	0.118
$250 \leq \mid\Delta\mid \leq 300$	2	0.118	3	0.176
$300 \leq \mid\Delta\mid \leq 350$	1	0.059	1	0.059
$350 \leq \mid\Delta\mid \leq 400$	2	0.118	0	0
$400 \leq \mid\Delta\mid \leq 450$	0	0	0	0
$450 \leq \mid\Delta\mid \leq 500$	1	0.059	0	0
$500 \leq \mid\Delta\mid \leq 550$	0	0	0	0
$550 \leq \mid\Delta\mid \leq 600$	2	0.118	0	0
$600 \leq \mid\Delta\mid \leq 650$	2	0.118	0	0
$650 \leq \mid\Delta\mid \leq 700$	1	0.059	0	0
$700 \leq \mid\Delta\mid \leq 750$	1	0.059	0	0
$750 \leq \mid\Delta\mid \leq 800$	1	0.059	0	0
$800 \leq \mid\Delta\mid \leq 850$	1	0.059	0	0

Overall prediction medium error: $m = \pm\sqrt{\frac{[\Delta\Delta]}{n-1}}$ = ± 536.34 mm.

Medium error of partition prediction: $m_{\text{partitio}} = \pm\sqrt{\frac{[\Delta\Delta]}{n-1}}$ = ± 170.80 mm.

Through comparative analysis, the median error of partition prediction is much smaller than that of the overall prediction. Therefore, the accuracy of partition prediction is higher and basically conforms to the actual situation, indicating that the key strata are not completely fractured and the hypothesis is valid.

7. CONCLUSION

Based on the research on the control of the surface deformation by the key stratum group of Gucheng Coal Mine, the following conclusions are obtained:

1. According to the stiffness and strength conditions of stratum lithology in Gucheng Coal Mine, the key strata and main key strata controlling surface deformation above No. 3 coal are determined, and the surface deformation is analyzed with the measured data.
2. Through the establishment of a large-scale separation of key strata mechanics model, the influence of deformation under key strata on surface deformation with the increase of the number of working faces in underground strip mining is calculated and analyzed.
3. The internal movement characteristics of rock mass in Gucheng Coal Mine Area are revealed by television imaging of surface borehole.
4. By judging the fracture distance of key strata, the method of probability integral method of multi-working face is put forward. Through the prediction of five working faces in Gucheng Coal Mine, the predicted results achieved are consistent with the actual situation.

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