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Law of surface movement for multi-coal seam strip mining

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Abstract: It is an important part of green mining to control the disasters of coal mining which have caused irreversible damages to buildings and ecological environment. Strip mining is one of the efficient measures to control surface subsidence and mining damage. However, the research on the laws of the surface subsidence are still deficient in multi-coal seam strip mining at present. Based on the Fast Lagrangian Analysis of Continua (short for FLAC3D) numerical simulation software, the laws of the surface subsidence and horizontal movement were systematically studied for different depths, different mining widths, different distances between seams, different mining thickness, different parameters between seams and the special relations of the upper pillar and the lower pillar in the vertical direction in multi-seam strip mining. The function relation between the maximum subsidence and the maximum horizontal movement with the depth, the mining width, the seam distance, mining thickness, different parameters between seams and the partial offset are summarized respectively. Finally the formula integrating the surface maximum subsidence value and the maximum horizontal movement was deduced. The results can be used for reference theory and measure in forecasting the surface displacement in multi-coal seam strip mining.

Keywords: multi-coal seam strip mining; FLAC3D; numerical simulation; surface maximum subsidence; surface maximum horizontal movement

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1 Introduction

Surface subsidence and environment disasters caused by coal mining which account for 70% in primary energy consumption have become increasingly prominent. A major challenge for mining subsidence is to exploit the utmost of underground resources on the premise of protecting the buildings on the ground effectively [1-2]. The key problem of mining under buildings is to control movement of rock strata and surfaces, which is also one of the main research
directions of subsidence issues[3]. At present, the main methods of controlling rock strata and surface movement include backfill mining, partial mining, abscission layer grouting, and so on. Strip mining has been extensively used in China for protecting buildings and ecological environment, safe production, control of increasing production cost and simple management, despite its low recovery rate compared with other mining methods.

Until now, there are plenty of theories and practical achievements about strip mining by scholars; however, most of them discuss about single seam strip mining[4]. The study and application of strip mining have increased year after year recently. There still exists some deficiency under the condition of design and practice of multi-seam strip mining[5-6]. First, predicting model and theory of surface subsidence with multi-seam strip mining are not constructed and the results of traditional prediction method is greatly different from the reality value[7]. Second, prediction parameter system of multi-seam strip mining are not established too and the way of choosing prediction parameters is in lack of reliable theory in surface movement calculated for multi-seam strip mining[8-9]. Last, the research of optimal design theory and layout model of multi-seam strip mining should be also improved[10-11]. Based on the Fast Lagrangian Analysis of Continuum (short for FLAC3D) numerical simulation software, we studied in this work the laws of the surface subsidence and horizontal movement were systematically studied for the different depth, different mining width, distance between seams, mining thickness, parameters between seams and the special relations of the upper pillar and the lower pillar in vertical direction (up and down coal pillar alignment or not) using FLAC3D simulation[12-15]. Numerical simulation models were built for the simulating purposes, which were continuous medium of the overlying rock strata inside, using displacement boundary condition of limiting horizontal movement in the four sides and two directions’ displacement at the bottom of model, and the top of it is free boundary. The stress caused by gravity, which is a hydrostatic state of stress, can only be considered in the process of calculation analysis, and the effects of tectonic stress on in-situ stress, rock initial stress depending on the load and property of overlying strata were neglected (See Fig. 1).

Fig. 1 Mechanical model of numerical simulation in strip mining

The chosen geological mining conditions for simulation purposes were as follows: mining depth from 200 m to 500 m, mining thickness between 1 m and 5 m, distance between seams from 10 m to 50 m, mining width ranging from 20 m to 50 m, the maximum change of parameters between seams being...
10 times, the thickness of floor being 40 m, coal seam being near horizontal and the extraction rate of design being 50%. The design mining district was 200 m by 400 m according to the strip width to make sure full mining of surface. The dimensions of designed basic model were 1200 m by 1000 m by 286 m to avoid edge effects, and the grids of strike, dip, and vertical direction were divided ranging from 5 m to 40 m in the light of simulating purpose, which had almost 35 882 units of each model. Mohr-Coulomb yield criterion was applied according to the mechanical property of overlying rock strata whose parameters were selected based on experiments in laboratory and work field (See Table 1).

2.2 Numerical simulation schemes

The effects of changes of mining depth, width, thickness, distance between seams and parameters between seams on surface subsidence and horizontal displacement were simulated respectively under the condition of the same recovery rate (50%) and up and down coal pillars alignment or complete stagger. On the basis of mining depth of 200 m, thickness of 3 m, distance of 40 m, and width of 20 m, one variable was varied in every simulation model and the others were the same as the basic quantity. (See Table 2)

3 Results and analysis of numerical simulation

3.1 Law of surface subsidence with multi-coal seam strip mining

3.1.1 Effects of mining depth on surface subsidence

The law of the maximum ground subsidence of mining depth was analyzed in the case of upper and lower coal pillars alignment and complete stagger. Relationship between the maximum ground subsidence and its coefficient with mining depth were obtained by regression analysis according to simulation data.

Alignment:

\[ w_0 = 0.718H - 24.8, \quad R^2 = 0.9648 \]  

where \( w_0 \) is the maximum ground subsidence, mm; \( H \) is the mining depth, m; and \( R \) is the correlation coefficient.

Complete stagger:

\[ w_0 = 0.781H - 37.1, \quad R^2 = 0.9814 \]  

Table 1 Rock parameters of simulation model

<table>
<thead>
<tr>
<th>Strata</th>
<th>K/GPa</th>
<th>G/GPa</th>
<th>C/MPa</th>
<th>( \phi )/°</th>
<th>T/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>alluvium</td>
<td>0.002</td>
<td>0.0004</td>
<td>0.01</td>
<td>20</td>
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<tr>
<td>Mudstone/sandstone</td>
<td>0.88</td>
<td>0.19</td>
<td>1.5</td>
<td>33</td>
<td>1.0</td>
</tr>
<tr>
<td>Siltstone</td>
<td>0.83</td>
<td>0.47</td>
<td>6.25</td>
<td>33</td>
<td>2.6</td>
</tr>
<tr>
<td>Main roof</td>
<td>0.74</td>
<td>0.51</td>
<td>8.56</td>
<td>37</td>
<td>3.0</td>
</tr>
<tr>
<td>Immediate roof</td>
<td>0.13</td>
<td>0.04</td>
<td>1.5</td>
<td>32</td>
<td>1.0</td>
</tr>
<tr>
<td>Coal seam</td>
<td>0.21</td>
<td>0.04</td>
<td>1.0</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>Coal seam floor</td>
<td>0.69</td>
<td>0.52</td>
<td>24.6</td>
<td>38</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Notes: \( K \) is the bulk modulus; \( G \) the shear modulus; \( C \) the cohesion; \( \phi \) the angle of friction; and \( T \) the tensile strength.
Table 2 Schemes of mining depth, width, thickness, interlayer spacing and lithology of alignment with upper and lower coal pillars

<table>
<thead>
<tr>
<th>Alignment</th>
<th>Scheme</th>
<th>Width /m</th>
<th>Depth/ m</th>
<th>Interlayer spacing /m</th>
<th>Thickness /m</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining depth of alignment and complete stagger</td>
<td>Model 1</td>
<td>20</td>
<td>200(^a)</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 2</td>
<td>30</td>
<td>300(^b)</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 3</td>
<td>40</td>
<td>400(^c)</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 4</td>
<td>50</td>
<td>500(^d)</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td>Mining width of alignment and complete stagger</td>
<td>Model 1</td>
<td>20</td>
<td>200</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 2</td>
<td>30</td>
<td>200</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 3</td>
<td>40</td>
<td>200</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 4</td>
<td>50</td>
<td>200</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
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<td>10</td>
<td>3</td>
<td>Constant</td>
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<tr>
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<tr>
<td></td>
<td>Model 4</td>
<td>20</td>
<td>200</td>
<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 5</td>
<td>20</td>
<td>200</td>
<td>50</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td>Mining thickness of alignment and complete stagger</td>
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<td>20</td>
<td>200</td>
<td>40</td>
<td>1</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 2</td>
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<td>200</td>
<td>40</td>
<td>2</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
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<td>40</td>
<td>3</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Model 4</td>
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<td>200</td>
<td>40</td>
<td>4</td>
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</tr>
<tr>
<td></td>
<td>Model 5</td>
<td>20</td>
<td>200</td>
<td>40</td>
<td>5</td>
<td>Constant</td>
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<tr>
<td>Interlayer lithology of alignment and complete stagger</td>
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<td>3</td>
<td>0.25</td>
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<tr>
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<td>20</td>
<td>200</td>
<td>40</td>
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<td>0.50</td>
</tr>
<tr>
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<td>Model 3</td>
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<tr>
<td></td>
<td>Model 4</td>
<td>20</td>
<td>200</td>
<td>40</td>
<td>3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

\(^a\)The depth is made up of 20 m alluvium, 90 m sandstone, and 90 m siltstone.

\(^b\)The depth is made up of 30 m alluvium, 135 m sandstone, and 135 m siltstone.

\(^c\)The depth is made up of 40 m alluvium, 180 m sandstone, and 180 m siltstone.

\(^d\)The depth is made up of 50 m alluvium, 225 m sandstone, and 225 m siltstone.
Alignment:

\[ q = 0.0001H - 0.0039, \quad R^2 = 0.9637, \quad (3) \]

where \( q \) is the subsidence factor.

Complete stagger:

\[ q = 0.00015H - 0.0063, \quad R^2 = 0.9802. \quad (4) \]

Increase in the stress of coal pillars and roof leads to the enlargement of the maximum surface subsidence along with mining depth expanding from above results. With the extent of stagger of upper and lower coal pillars increasing, the maximum ground subsidence added caused by the larger stress of upper coal pillar impacting on the lower goaf which brought about a larger curvature of the roof of lower coal seam and the relationships between the value of subsidence and the mining depth were linear.

3.1.2 Effects of mining width on surface subsidence

Relationship between the maximum ground subsidence and the mining width was obtained by regression analysis according to simulation data.

Alignment:

\[ w_0 = 34.784e^{0.064b}, \quad R^2 = 0.9920, \quad (5) \]

where \( b \) is the mining width, m.

Complete stagger:

\[ w_0 = 33.106e^{0.0624h}, \quad R^2 = 0.9951. \quad (6) \]

Curvature value of the roof increased along with the augmenting of mining width under the same stress, which caused a larger ground subsidence according to regression analysis of different mining width. Under the condition of the same width, the ground subsidence became larger following the expansion of stagger extent of upper and lower coal pillars which caused the stress of lower roof increased and its bending value enlarged too. Therefore the larger the mining width, the more effects of stagger extent on settlement on account of the longer roof exposure.

3.1.3 Effects of distance between up and down coal seams on surface subsidence

Functional relations between the maximum ground subsidence and the distance between up and down coal seams were obtained by regression analysis according to simulation data.

Alignment:

\[ w_0 = 184.66h^{0.0402}, \quad R^2 = 0.8852. \quad (7) \]

where is \( h \) the distance between up and down coal seams, m.

Complete stagger:

\[ w_0 = -39.597\ln(h) + 370.89, \quad R^2 = 0.9884. \quad (8) \]

Ground subsidence tended to have small an increment along with the augmenting of distance between up and down coal pillars under the condition of alignment according to regression analysis of different interlayer spacing. However, when upper and lower coal pillars completely stagger, the law of surface movement was opposite because bending rigidity of the rock beam increased, leading to small bending value of lower roof and decreased surface subsidence.

The relationship between stagger extent and maximum subsidence under the same interlayer spacing showed that a smaller spacing a larger effects on stagger extent of upper and lower coal pillar-and vice versa. There was less effects of stagger extent on the maximum settlement until the interlayer spacing reaching at 40m. At this time, the effects of distance on spatial relationship between upper and lower coal pillars can be neglected.
3.1.4 Effects of mining thickness on surface subsidence

Relationship of the maximum ground subsidence with mining thickness was obtained by regression analysis according to simulation data. Alignment:

\[ w_i = 70.509 e^{0.303 m}, \quad R^2 = 0.9932, \quad (9) \]

where \( m \) is the mining thickness, m.

Complete stagger:

\[ w_i = 74.633 e^{0.303 m}, \quad R^2 = 0.9928. \quad (10) \]

The value of subsidence became larger with a larger mining thickness in alignment and complete stagger. It increased faster after the mining thickness was greater than 3 m. Subsidence factor presenting upward parabola was at the bottom when the mining thickness was 3 m because rock fracture of above goaf could reach a certain height and stopped for the existing key stratum when the area of strip mining was small, which caused the goaf unable to be filled fully. For this reason, the height of mining had less effect on the surface subsidence. However, the subsidence coefficient increased quickly and the stability of coal pillars decreased when the mining thickness was more than 3 m (such as 4 m and 5 m).

3.1.5 Effects of interlayer lithology on surface subsidence

Relationship between the maximum ground subsidence and interlayer lithology was obtained by regression analysis according to simulation data. Alignment:

\[ w_i = 1122 E^{0.087}, \quad R^2 = 0.9932, \quad (11) \]

Complete stagger:

\[ w_i = 1426.6 E^{0.0972}, \quad R^2 = 0.9705. \quad (12) \]

where \( E \) is the elasticity modulus of interlayer strip mining, Pa.

The maximum surface subsidence was power functional relation of interlayer lithology. The value of settlement decreased and tended to be constant with the lithology increased because the harder lithology of medium rock, the lower height of immediate roof fracture caused by mining lower coal seams. So the lower mining had less effect on the stability of upper coal pillars and it will benefit preventing surface settlement.

Synthesizing the effects of above five factors on the surface subsidence, a comprehensive expression can be as follows. Alignment:

\[
q = -1.455 \times 10^{-2} + 7.13 \times 10^{-3} \ln(h) + 3.19 \times 10^{-3} (m - 3.055) + E^{-1.73 \times 10^{-3}} + e^{2.98 \times 10^{-7} b - 1.40 \times 10^{-4} H}, \quad R^2 = 0.939. \quad (13)
\]

Complete stagger:

\[
q = 1.825 \times 10^{-2} + h^{-1.73 \times 10^{-3}} + 3.474 \times 10^{-3} (m - 2.930) + E^{-2.11 \times 10^{-3}} + e^{1.99 \times 10^{-7} b - 1.48 \times 10^{-4} H}, \quad R^2 = 0.934. \quad (14)
\]

3.2 Law of surface horizontal displacement with multi-coal seam strip mining

Taking the strike as an example, the functional expressions between individual factors with the maximum horizontal displacement were not presented for the length of paper, but the comprehensive expressions were given at last.

3.2.1 Effects of mining depth on surface horizontal displacement

The maximum horizontal displacement had an approximately linear relation with the mining depth by
regression results of simulation, which showed that the surface displacement increased along with the adding of depth leading to the thickness of beam bending expanding.

The maximum surface horizontal displacement became larger with the stagger extent of upper and lower coal pillars increasing at the constant depth. It increased faster when the stress of coal pillars and roof increased leading to a larger curvature of the roof of the lower coal seam.

3.2.2 Effects of mining width on surface horizontal displacement

The relation between mining width and surface horizontal displacement was exponential and the displacement increased with the increase of width in the upper and lower coal pillars alignment and complete stagger, as shown from the regression analysis. Because the curvature of the roof increasing along with the augmenting of mining width caused ground subsidence.

Under the condition of the same width, the maximum surface displacement became large following the stagger extent expanding of upper and lower coal pillars which caused the stress of lower roof increased and its bending value enlarged too. Therefore, the larger mining width, the more effects of stagger extent on settlement on account of longer roof exposure.

3.2.3 Effects of distance between up and down coal seams on surface horizontal displacement

Ground horizontal displacement tended to increase along with the augmenting of the distance between up and down coal pillars under the condition of alignment according to regression functions of different interlayer spacing. However, when the upper and lower coal pillars completely stagger, the law of surface horizontal displacement was opposite because the horizontal displacement caused by upper coal seam mining overlaid the lower one, which decreased the comprehensive movement after both coal seams were mined. The less spacing, the larger effects on stagger extent of upper and lower coal pillars; and vice versa. The simulation results showed that effects of stagger extent on the maximum displacement could be neglected until the interlayer spacing reaching a certain distance.

3.2.4 Effects of mining thickness on surface horizontal displacement

The value of displacement accelerated with the mining thickness adding when alignment and complete stagger. The increment became lager after mining thickness greater than 3m and the mining thickness is exponential relation with the maximum horizontal displacement. When the mining thickness is small, the effects of mining can’t transfer to surface for the existing of key stratum. However, the rock fracture height become large while mining thickness increasing, which will destroy the stability of pillars. So the displacement becomes enhancement quickly.

3.2.5 Effects of interlayer lithology on surface horizontal displacement

The maximum horizontal displacement was a linear relation of interlayer lithology. The value of displacement decreased with the lithology increasing but the variation is a little away from alignment to complete stagger. Because the variable lithology was concentrating in the interlayer rock strata, the lower coal mining did not affect the stability of upper coal pillars.

Synthesizing the effects of above five factors on surface subsidence, a comprehensive expression can be as follows.

Alignment:
\begin{align*}
b &= -3.1 \times 10^{-2} - 5.053 \times 10^{-3} \ln(h) + \\
& 1.9773 \times 10^{-5} (m - 2.1346)^2 + 1.577 \times 10^{-2} \ln(E) + \\
& 3.87 \times 10^{-5} (B - 22.1429)^2 + 2.167 \times 10^{-2} \ln(H), \\
R^2 &= 0.900. \quad (15)
\end{align*}

Complete stagger:

\begin{align*}
b &= 3.25 \times 10^{-2} + 5.066 \times 10^{-1} h^{-2} + 2.113 \times 10^{-3} (m - 2.6818)^2 + \\
& 1.57 \times 10^{-2} \ln(E) + 4.153 \times 10^{-5} (B - 23.333)^2 + \\
& 2.202 \times 10^{-2} \ln(H), \quad R^2 = 0.885. \quad (16)
\end{align*}

4 Conclusions

1) The surface subsidence and horizontal displacement hold an exponential relation with the mining thickness. The value of subsidence and displacement becomes large with mining thickness increased. However, the relations between subsidence coefficient, horizontal coefficient and mining thickness are a quadratic polynomial function; when mining thickness is 3 m, the values of them reach at the bottom.

2) The relationships between surface subsidence, horizontal displacement and interlayer lithology are exponential and linear respectively. The values of subsidence and displacement become larger with the lithology decreased. However, the variation of horizontal displacement is a little away from alignment to complete stagger.

3) The function relations between surface subsidence and displacement with the five factors in alignment and complete stagger state were given.

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