Study on the shear movement law of overlying strata by slice mining

Junhui Fu1,2,3 | Guangcai Wen1,2 | Haitao Sun2,3 | Xuelin Yang2,3,4

Abstract

Based on the analysis of shear movement characteristics of overlying strata under mining effect, a quantitative calculation model for shear displacement in the along-strike and down-dip directions of the overlying strata is established. The shear displacement at any point on the interface of overlying strata in composite rock beam under slice mining is analyzed. The evolution law of shear displacement and deformation of the overlying strata with the advancement of working face was inverted by physical simulation test. The results show that the shear movement of the overlying strata is characterized by a repeated pattern of “increase → decrease → increase → decrease.” The shear displacement of the overlying strata increases gradually after slice mining. The shear displacement of the overlying strata is in the shape of “W” after the lower seam mining, and the maximum shear displacement of the overlying strata by the lower seam mining is 1.67 times of that of the overlying strata after the upper seam mining. Field test of shear movement of the overlying strata was conducted on the panel 4308 of Chengzhuang coal mine. The results show that the shear displacement of the overlying strata above the coal seam increases with the burial depth. And the shear displacement of the overlying strata movement after mining has “time-delay” effect. The larger the depth of the measuring point is, the larger value of the along-strike shear displacement is. The breakage of the key strata of the overlying strata will cause the shear displacement of the overlying strata to increase rapidly. And there is a demarcation depth (127.98 m) for the shear displacement of the overlying strata. The shear movement of the overlying strata above the dividing point is not obvious, while the shear movement of the overlying strata below the dividing point is in the shape of “S” (amplitude of 50 mm). When the working face advanced beyond the test well, the overlying strata would experience multiple shear movement. When the working face advanced 34-100 m ahead of the surface test well, the overlying strata experienced the most severe shear displacement. When the working face advanced to 74 m away from the surface test well, the shear displacement of the overlying strata between 10# (depth of 192.01 m) and 16# (depth of 300.07 m) is larger than that at the upper position, and down-dip shear displacement is the most severe (about 315 mm). The shear displacement of the overlying strata is coincident
1 | INTRODUCTION

Longwall mining will lead to significant disturbance of the overlying strata directly above the extracted gob of each longwall panel. Slicing mining method is widely employed for thick seam in Shanxi, Xinjiang, and other provinces of China, which usually results in severe shear displacement of the overlying strata and severe ground subsidence,1 and even mining disasters, such as groundwater influx and rock burst.2-4 Especially, a competent stratum may slide along the abutment before achieving stable voussoir beam structure.5,6 The shear effect of slicing mining on the overburden in the stope will cause severe shear deformation damage to the surface well casing, as shown in Figure 1.

Ma and Hu7 pointed out that slice mining would accelerate the speed of surface subsidence and intensify the surface destruction. Ma et al8 studied the movement of the overlying strata and water conductive fractures (WCF) under conditions of repeated mining in short-distance coal seams by physical simulations and field measurements. The results show that, due to the impact of repeated mining in short-distance coal seams, WCF in the overlying strata at the edge of the mined-out area are connected to the Quaternary loose aquifer and are not likely to close, resulting in the loss of the water resource. Wang et al9 indicated that the height of overburden crack belt reduced along with the increase of gob development time in repeated mining of thick coal seam. Xie et al10 proposed that the mining stress borderline of the lateral roadway extended 91.7 m outward after repeated mining. Then, the original stress increased, deforming the roadway of interest, which agreed with the in situ observations. Tajduś11 indicated that the following factors, inter alia, influence the distribution of horizontal displacement: the position of a given point in relation to exploitation, rock mass properties, hydrogeological conditions, tectonics, depth of exploitation, thickness of excavated deposit, method of exploitation, or speed of mining performance.

Various theories pertaining to the determination of mining-induced horizontal displacement are discussed, followed by a complex study on horizontal displacements measured for a selected example region of the German coal mine BW Prosper Haniel, as well as the determination of displacement factor B.12,13 Daigle and Mills14,15 proposed that an inclinometer monitoring would provide significant insight into the mechanics of the ground movements in response to longwall mining. Mills et al16-18 found that the shear movement of the overlying strata was generally oriented toward the longwall face, but more parallel to the main shear stress. Liu et al19-21 constructed a calculation method for the movement of the overlying strata under the influence of a single mining and analyzed the stability of the surface well extraction.

FIGURE 1 Shear failure of surface well casing in the overlying strata caused by slice mining

with the along-strike shear displacement, and the down-dip shear displacement is smaller than the along-strike shear displacement. This research provides theoretical guidance for the design of shale gas or coalbed methane surface wells and coal mine shaft under slice mining.

KEYWORDS
mining influence, shear movement, slice mining, surface well
To sum up, the researchers have studied the water conductive fractures, gob stability, and stress transfer under repeated mining, and analyzed the shear movement characteristics of the overlying strata under the influence of single seam mining. However, there is no relevant research report on shear displacement of the overlying strata under slice mining. Recently, the surface well technique is frequently used for gas extraction in many coal mines. And the surface well may be damaged by the movement of the overlying strata under slice mining. Therefore, it is necessary to study the shear movement of the overlying strata by slice mining.

The purpose of this paper is to study the shear movement law of the overlying strata by slice mining and guide the design of surface well and roof high-level borehole in mining area. In order to obtain the shear movement of the overlying strata under slice mining at different times, a model of movement of the overlying strata based on time delay is established. In order to verify the correctness of the theoretical model, physical simulation test was used to monitor the shear movement of the overlying strata by slice mining, and shear displacement law of the overlying strata was analyzed with the advancement of working face. In order to verify the correctness of theoretical analysis and simulation experiment, a test well was arranged in panel 4308 to monitor the shear displacement of the overlying strata.

2 | ANALYSIS OF SHEAR MOVEMENT OF THE OVERLYING STRATA UNDER THE INFLUENCE OF SLICE MINING

2.1 Characteristics of ground and the overlying strata subsidence by slice mining

The process of ground and the overlying strata subsidence under the influence by slice mining is shown in Figure 2. It is noted that positions 0, 1, and 2 represent the position of the cut hole, the middle of the stope, and the stopping line, respectively. \( W_1 \) and \( W_2 \) represent the settlement curves from the upper layer mining to the middle of the stope and the end of mining. \( W_3 \) and \( W_4 \) represent the settlement curves from the lower layer mining to the middle of the stope and the end of mining. When the upper seam is mined to position 1, the ground subsidence curve is \( W_1 \); when the upper seam is mined to position 2, the ground subsidence curve gradually changes from \( W_1 \) to \( W_2 \). When the lower seam is mined to position 2, the ground subsidence curve gradually changes from \( W_3 \) to \( W_4 \).

2.2 Shear movement of the overlying strata by slice mining

Underground coal mining usually adopts the along-strike mining method. Down-dip coal seam mining is rarely used. Therefore, the unloading and release rock beams in the down-dip direction can be regarded as instantaneous. As the size of the mined space increases, the mining influence radius gradually increases. When the semi-infinite mining status is reached, the mining influence radius is basically stable at a certain value. Therefore,

\[
\begin{align*}
V &= v \quad \text{(Semi - infinite mining)} \\
V &= a \cdot v \quad \text{(Limited mining)}
\end{align*}
\]  

where \( V \) is the movement speed of the mining influence radius in the along-strike direction \( v \); the mining speed of the working face; and \( a \) is a dimensionless parameters related to mining speed, overlying strata parameters and mining methods.

Generally, the maximum subsidence displacement is reached after one or two years of slow subsidence. The subsidence of the overlying strata has time hysteresis. Therefore, the time hysteresis coefficient \( C \) is introduced to describe the subsidence of the overlying strata and shear displacement hysteresis.

\[
C = \frac{t_c}{T_c} = \frac{2r_y}{\sqrt{V}}
\]

where \( C \) is the time hysteresis coefficient, \( C \leq 1 \); \( t_c \) is the time used to mine over twice the influence radius \( 2r_y \) of the face at a given mining speed; and \( T_c \) is the actual time used to reach the maximum overlying strata subsidence.

Using Euler method and Lagrange method, the shear displacement at any point on the interface of the equivalent composite strata can be expressed by Formula (3) at a certain time. Formula (3) can describe the distribution status for different positions of the object of study. For an interface between equivalent composite overlying strata, the layer of a point on the shear displacement change along with mining can be analyzed using the Lagrange method. The calculation of shear displacement at any point on the interface of composite rock beam is shown in formula (3).
where \( h_1 \) is the thickness of the upper seam of the equivalent composite strata; \( w_{\text{max}} \) is the maximum subsidence displacement of the strata; and \( r_Y \) is the mining influence radius.

When the strata subsidence caused by mining develops with the advance of the working face, coordinate XO’Y (Figure 3) moves forward as mining advances at speed \( V \), which can be equivalent to the change in positions of the relative coordinate origin of a point on the interface of composite rock beam with time. The shear displacement of the overlying strata at a certain point on the interface of composite rock beam strata can be obtained relative to time.

In previous models, \( C_1 V t_1 = x_1 \) gives the XOY coordinate values under the influence of the upper seam mining. Under the condition of thick seam slice mining, the overlying strata will undergo several shear movements. The repeated shear movement will occur at any point on the interface of strata in composite rock beam. According to superposition of displacement, the shear displacement of the overlying strata at different times under slice mining can be obtained by iterative summation.

\[
\begin{align*}
\{ u(z_2) &= \frac{2C_2 h_1 w_2}{r_{t_2}} e^{-\frac{(z - r_{t_2})^2}{r_{t_2}^2}} \quad \text{(Semi - infinite mining)} \\
\} u'(z_2) &= \frac{2C_2 h_1 w_2}{r_{t_2}} \left[ e^{-\frac{(z - r_{t_2})^2}{r_{t_2}^2}} - e^{-\frac{(z - r_{t_2} - l)^2}{r_{t_2}^2}} \right] \quad \text{(Limited mining)}
\end{align*}
\]

In the down-dip direction, the width of the mining influence is generally much larger than the thickness of strata. The equivalent strata model can be used to analyze the deformation characteristics of strata in a small along-strike segment. Similarly, in the along-strike direction, the width of the mining influence range is generally much larger than the thickness of strata. Therefore, the equivalent strata model can be used to analyze the deformation characteristics of the strata in the along-strike direction in a small down-dip section (Figure 4).

In the course of the overlying strata movement, settlement and interlayer slip deformation occur simultaneously between along-strike rock beam and down-dip rock beam. The spatial relationship of interlayer slip between the slip planes
is shown in Figure 5. Under the influence of slice mining, the shear displacement of the overlying strata at any point on the interface of strata in composite rock beam is given by formula (6).

\[ u(x,z,t) = [u(x_2)^2 \cos^2 \varphi + u(z_2)^2]^{1/2} \]  

(6)

where the values of \( u(x_2) \) and \( u(z_2) \) are determined by Equations (4) and (5), respectively. The \( \cos \varphi \) is the dip cosine value of the relative initial position of the overlying strata after interlayer slip, \( \cos^2 \varphi = \frac{1}{1+w'z_x} \); \( w'(x) \) is the derivative of the rock subsidence displacement function.

Based on the above literature review and theoretical derivation, the shear movement model of the overlying strata based on time-delay effect is established, which can predict the shear displacement of the overlying strata under slice mining.

3 | PHYSICAL SIMULATION OF THE SHEAR DISPLACEMENT OF THE OVERLYING STRATA BY SLICE MINING

In order to verify the validity of the theoretical analysis, the shear movement law of the overlying strata by slice mining was quantitatively analyzed by physical simulation test.

3.1 | Model establishment

A two-dimensional physical simulation test system is adopted, which is composed of a steel frame system, loading system, stress test system, and displacement test system. The frame is 3 m × 0.4 m × 2 m, and the effective height is 1.8 m. The size of the test model is 3 m × 0.4 m × 1.58 m.

Physical simulation conditions were mainly based on the geological conditions of the Chengzhuang coal mine in the Shanxi Jincheng Anthracite Coal Mining Group. According to the mechanical properties of coal and strata, a simulation model was established using similar materials.

Suppose the dimensions of the three directions of the prototype are \( X_p, Y_p, \) and \( Z_p \), the corresponding dimensions of the model are \( X_m, Y_m, \) and \( Z_m \), and take the length similarity coefficient as \( C_L = Y_m/Y_p = Z_m/Z_p = 1/100 \). The similarity
coefficient of time is $C_t = \frac{T_p}{T_f} = \sqrt{\frac{C_L}{C_{pi}}} = 1/10$. The density of layer I in the prototype is $\gamma_{mi}$; and the density similarity coefficient is $C_{\gamma} = \frac{\gamma_{mi}}{\gamma_{pi}} = 1/1.5$. The density of each layer in the model is $\gamma_{pi} = \frac{\gamma_{mi}}{1.5}$. Suppose the elastic modulus of the prototype material is $E_{pi}$ and the elastic modulus of the material model is $E_{mi}$, then the similarity coefficient of the elastic modulus of each layer is $\frac{E_{pi}}{E_{mi}}$. The density of each layer in the corresponding model is $\frac{\gamma_{mi}}{\gamma_{pi}} = 1/150$.

Suppose the unidirectional compressive strength of the prototype material is $\sigma_{ci}$, the corresponding uniaxial compressive strength of the model material is $\sigma_{emi}$; and the unidirectional compressive strength of each layer of the material in the model is $\sigma_{emi} = \frac{\sigma_{ci}}{150}$.

A WinCE(R) series total station was used to monitor shear displacement of the overlying strata. The parameters of displacement monitoring equipment are shown in Table 1.

Before the experiment, the initial coordinates were measured, and then the displacement of the measuring points was obtained by subtracting the measured coordinates from the initial coordinates. Due to the limitation of the model size, 21 pieces of steel plates are uniformly arranged above the model for the unpaved overlying strata in the model. The bottom area of steel plate is 400 mm × 142 mm. And the weight of each steel plate is 10 kg. Figure 6 (A) shows the test model. Figure 6 (B) shows model lithology and layout of measuring points in the model.

### 3.2 Simulation scheme

First, extract the upper seam (30 mm thick). Then, extract the lower seam (30 mm thick) after the overlying strata is roughly stable. The left and right boundaries of both models were left with 300 mm in order to minimize the impact boundary conditions (Figure 6B). In order to avoid the rapid collapse of the upper strata during lower seam mining, steel sheets are installed at the bottom after the upper seam is mined, and the strips are lifted gently to mine the lower seam. The steel sheet is 50 cm long, 8 cm wide, and 0.2 cm thick. Layout of steel sheets by slice mining is shown in Figure 7.

The working face is advancing from left to right (Figure 6B). The width of the open-off cut is 100 mm, and each advancing length of working face is 80 mm each time. The time interval of each mining is two hours in this model. The deformation of the overlying strata during the upper seam and lower seam mining is shown in Figures 8 and 9.

### 3.3 Physical simulation results analysis

The total station monitoring system has monitored the movement of the overlying strata at 145 measuring points and selected 15 representative measuring points for analysis according to the needs of the research on the shear movement of the overlying strata. The layout of measuring points is shown in Figure 6B.

Figure 10 shows the shear movement of the overlying strata during the upper seam mining. In this model, it is defined that the shear deformation of overlying strata from left to right is positive (consistent with the advancing direction of the working face). Otherwise, it is negative (opposite to the advancing direction of the working face).

1. The shear displacement of the overlying strata during upper seam mining.

   The shear movement of the overlying strata during the upper seam mining mainly occurs in the opposite direction of the advancing direction of the working face, that is, the left side of the model. Before the working face advanced 1200 mm, no shear displacement occurs in the overlying strata 750 mm above the coal seam, but the shear displacement of the overlying strata from 150 mm to 550 mm above the seam occurs on the left side of the model. When the working face advanced 1360 mm, the all the overlying strata above the seam have shear displacement on the left side of the model, and the maximum shear displacement of the strata 950 mm above the coal seam is 12 mm. After the

| Equipment name | Southern total station | Measurement system | Fundamental frequency 150 MHz |
|----------------|------------------------|--------------------|-------------------------------|
| Equipment type | NTS-391R10             | EDM type            | Coaxial                       |
| Operating system | Windows CE             | Accuracy            | ±0.00 1 mm                    |
| Ranging method | Standard deviation of ranging | Measurement time |                              |
| Prism precision measurement | ±(1 + 1 × 10⁻⁶·D) mm | < 0.5 s             |                              |
| Prism tracking | ±(5 + 2 × 10⁻⁶·D) mm  | < 0.1 s             |                              |
| Reflector      | ±(1 + 1 × 10⁻⁶·D) mm  | < 0.5 s             |                              |

**TABLE 1** The parameters of the displacement monitoring equipment
working face advanced 1360 mm, the shear displacement of the overlying strata moves to the right side of the model. When the working face advanced about 1700 mm, the strata layer 950 mm above the coal seam first returns to the original position. After the working face advanced 1700 mm, the shear displacement of the overlying strata continues to develop to the right side of the model. When the working face advanced 2200 mm, the shear displacement of the overlying strata reaches the maximum (4 mm). When the working face advanced 2400 mm, the upper seam is finished, and the shear displacement of the overlying strata moves to the left side of the model.

The overlying strata movement is characterized by a shear displacement pattern of "increasing → decreasing" during the upper seam mining, and the shear displacement curve forms a "V" shape. Because the overlying strata did not reach a stable state, the shear displacement is approximately 5 mm toward to the left side. The shear displacement of the
overlying strata 1200 mm from the cut hole (Figure 10B) and 1900 mm from the cut hole (Figure 10C) is similar to that of 500 mm from the cut hole. The nearer the measuring point is to the coal seam, the larger the shear displacement of the overlying strata is.

(2) The shear displacement of the overlying strata during lower seam mining.

The shear displacement of the overlying strata first turns to the left side of the model and then to the right side of model. When the working face advanced 340 mm in lower seam, the shear displacement of the overlying strata to the left side reaches the maximum value (about 20 mm) (Figure 10A). When the working face reached 1300 mm, shear displacement of the overlying strata returns to the original position. As the working face advanced to the end, shear displacement (about 3 mm) in the overlying strata shifts first toward the right side of the model and then to the original position. The overlying strata movement is characterized by a shear displacement pattern of “increasing → decreasing” during the lower seam mining. The shear displacement curve of the overlying strata forms a “W” shape after slice mining. The maximum shear displacement of the overlying strata by the lower seam mining is 1.67 times of that of the overlying strata by the upper seam mining.

From the above analysis, the overlying strata movement during slice mining is mainly characterized by the repeated dislocation movement of shear displacement with a pattern of “increase → decrease→increase → decrease” (Figure 11). Before upper seam mining, the shear displacement line is vertical (Figure 11A). When the working face advanced 1360 mm in upper seam mining, the shear displacement of the overlying strata to the left side increases to the maximum value (Figure 11B, u1). When the working face advanced 2400 mm, the shear displacement decreases to u2 (Figure 11C, u1 > u2). When the working face advanced 340 mm in lower coal seam, the shear movement of the overlying strata will reach u3 (Figure 11D) (maximum value of mining
FIGURE 10  
Shear displacement of rock strata under the influence of slice mining. (A) Shear displacement of five measuring points at 500 mm from the cut hole. (B) Shear displacement of five measuring points at 1200 mm (in the middle of the model) from the cut hole. (C) Shear displacement of five measuring points at 1900 mm from the cut hole.
stage). After the working face in lower seam mining, the shear displacement of the overlying strata decreases to \(u_4\) (Figure 11E, \(u_3 > u_4\)).

The above analysis verifies or improves the shear displacement motion pattern of theoretical analysis. However, due to the limitation of the size of similar physical simulation model, the theoretical analysis cannot be used to determine the shear displacement amount at any point in the model. This paper will verify the amount of shear displacement at any point in the theoretical analysis in a field test.

4 | FIELD TEST OF SHEAR MOVEMENT OF THE OVERLYING STRATA

In order to verify the theoretical model of shear displacement of the overlying strata, shear displacement of the overlying strata was monitored. However, the second coal seam should be mined about 1.5 years after the upper seam coal extraction, and current shear displacement monitoring system cannot meet this time requirement. Therefore, in this test, just the
monitoring of shear movement of the overlying strata during upper seam mining was conducted.

4.1 | Test layout

The north of panel 4308 in Chengzhuang coal mine in China is mined-out area, the south is unexploited coal seam, the east is unexploited coal seam, and the west is gob. The 3# coal seam was the mining seam and has a depth of 378 m, total coal seam thickness of 6.25 m, and dip angle of 2-8°. The along-strike length of the working face is 819 m. The test well is 247 m away from the cutting hole and 80 m away from tailgate, as shown in Figure 12.

4.2 | Test method

A well inclinometer was used to monitor the movement of the overlying strata. Fixed inclinometer probes were deployed in series with connecting rods in different layer before movement of the overlying strata, and the end of connecting rods were suspended at the orifice of test well. During the overlying strata movement, the inclinometer monitors the inclination of test section, and the deformation can be obtained from the inclination values of the two measuring points.28 The fixed inclinometer system can be used to obtain the overlying strata displacement from initial mining to the overlying strata stability (Figure 13).

A dual-axis fixed inclinometer sensor (C12-1.9) was used to monitor shear movement of the overlying strata. The sensor value range is −15° to + 15°. The sensor can simultaneously monitor two orthogonal displacement directions. There are two pairs of vertical guide grooves in the tube. Each tube is 3 m long, and the two adjacent tubes are closely connected by pipe joints.

The surface well of panel 4308 was selected as the test well for the inclinometer sensor. Test well diameter was 100 mm, and the locations of the inclinometer sensor are shown in Figure 14.
The main direction of the fixed inclinometer is consistent with the direction of panel 4308. In order to ensure that the inclinometer is always in a free vertical suspension state in the inclinometer tube, the top connecting rod should be suspended at the orifice, and the connecting rod should be suspended using self-made device (Figure 15). The data acquisition and transmission system of the fixed inclinometer are shown in Figure 16.

4.3 | Test result analysis

4.3.1 | Along-strike shear movement of the overlying strata

The variation of shear displacement of the overlying strata with different depth is shown in Figure 17.

(1) Before the working face advanced to the test well.

When the working face advanced to 149 mm from the surface test well, the shear displacement (about 40 mm) occurs below the 6# measuring point (depth of 127.98 m) (Figure 17A). When the working face advanced 126 m, the shear displacement of the overlying strata increased to approximately 90 mm. When the working face advanced 88 m away from the surface test well, the shear displacement of the overlying strata reduced to approximately 40 mm. When the working face advanced to 45 m away from the surface test well, the shear displacement increased to 80 mm. When the working face advanced to the surface test well, the shear displacement reduced to 70 mm. Before the working face advanced to the test well, with the advancement of the working face, the shear displacement above the 6# measuring point (depth of 127.98 m) is not obvious. The along-strike shear displacement of the strata below 6# measuring point (depth position of 127.98 m that is demarcation point) takes the form of "S" with an amplitude of 50 mm.

(2) When the working face advanced beyond the test well.

When the working face advanced beyond test well, the shear displacement is not obvious immediately, because the overlying strata movement has "time-delay" effect. When the working face advanced to 34 m to 94 m beyond the test well, the overlying strata underwent severe shear displacement. When the working face advanced to 74 m away from the surface test well, the shear displacement of the overlying strata between 10# (depth of 192.01 m) and 16# (depth of 300.07 m) is larger than that at the upper position. And the larger the depth of the measuring point is, the larger value of the along-strike shear displacement is. The shear displacement of the overlying strata at the measuring point of 16# (depth of 300.07 m) reached the maximum value (about 550 mm), which is caused by the breakage of the key strata between 9# (depth of 166.23 m) and 10# (depth of 192.01 m) measuring points. After the working face advanced to 115 m beyond the surface test well, the shear displacement of the overlying strata shifts to the side of the stopping line. As the working face advanced 194 m, the overlying strata below 10# measuring points (depth of 166.23 m) has a shear displacement from the cut hole direction (left side) to the stopping line direction (right side). The range of shear displacement of the overlying strata tended to decrease after the working face advanced 194 m beyond test well. When the working face advanced 445 m beyond test well, the larger the overlying strata depth is, the larger the shear displacement is. When the working face advanced 445 m beyond test well, the shear displacement of the overlying strata at the lowest measuring point (16 measuring points, depth of 300.07 m) is 310 mm.

After the working face advanced to the surface test well, the shear displacement of the overlying strata displays a repeated dislocation process (Figure 17B). When the working face advanced ahead 34 m-100 m of the surface test well, the shear displacement of the overlying strata is the most severe. The farther the working face is from the surface test well, the smaller the shear displacement of the overlying strata is. The ratio of the upper and lower maximum shear displacement amplitudes is about 1:0.7.

Figure 17 shows the distance between the working face and the surface well, and the negative value indicates that the
working face has not advanced to the position of the surface well. The positive value indicates the position of the working face passing through the surface well.

According to formula (5), the along-strike shear displacement of the overlying strata at 96.7 m, 192.01 m, and 292.6 m depth is calculated (Table 2).

When \( C_1 V_1 t_1 \geq r_{Y_0} \) and \( C_1 V_1 t_1 - r_{Y_0} \to 0 \), then \( e^{-\frac{C_1 V_1 t_1 - r_{Y_0}}{r_{Y_1}}} \to 1 \), so \( e^{-\frac{C_1 V_1 t_1 - r_{Y_1} - l_i}{r_{Y_1}}} \to 0 \). So formula (5) simplifies to \( u^*(x_1) = u^*(t_1) = \frac{2h_1(w_1 - w_2)}{r_{Y_1}} \).

Therefore, when the depth of the overlying strata is 96.7 m, the overlying shear displacement \( u^*(x_1)_1 \) is 166 mm. When the depth of the overlying strata is 192.1 m, the overlying shear displacement \( u^*(x_1)_2 \) is 205 mm. When the depth of the overlying strata is 292.6 m, the overlying shear displacement \( u^*(x_1)_3 \) is 289 mm.

According to the measured data of the overlying strata shear displacement, when the working face advanced over the cut hole 445 m, the measured shear displacement of the overlying strata at 96.7 m, 192.01 m, and 292.6 m is 58 mm, 172 mm, and 310 mm, respectively. There is a good
correspondence between the theoretical calculation and the measured data, but there is a certain deviation due to the complexity of the overlying strata in the stope. Both the theoretical calculation and the measured data show that the larger the depth is, the larger the shear displacement is.

### 4.3.2 Down-dip shear movement of the overlying strata

Figure 18 shows the variation of down-dip shear movement of the overlying strata at different depths measuring points with working face advances.

Before the working face was mined to the surface test well. When the working face advanced to the surface test well, small shear displacement of the overlying strata occurs. The overlying strata produces shear displacement toward both the headgate and tailgate, and the shear displacement of the overlying strata toward the headgate side and reached the maximum value (about 40 mm).

(2) After the working face advanced beyond the surface test well.

When the working face advanced to the vicinity of the surface test well, the strata above the 9# measuring point (166.23 m depth position) shows obvious shear displacement to the headgate side. When the working face passed the test well 74 m-115 m, the shear displacement of the overlying strata toward the headgate side and reached the maximum value (about 40 mm).

When the working face advanced beyond the test well from 115 m to 154 m, shear displacement (about 100 mm displacement) was toward the headgate.

When the working face advanced beyond the surface test well from 154 m to 194 m, shear displacement on the side of the tailgate returned to the original position. When the working face advanced beyond the test well from 115 m to 194 m, the area around the 9#-10# measurement points (with depth of 166.23 m-192.01 m) slowly returned to the tailgate side (right side) near the original position.

When the working face advanced 194 m beyond the test well, the shear displacement of the overlying strata returns to the vicinity of test well. When the working face advanced beyond the area of the test well from 395 m to 445 m, the whole overlying strata shifted toward the headgate with a displacement of approximate 200 mm.

Results shows that the shear displacement of the overlying strata is coincident with the along-strike shear displacement, and the down-dip shear displacement is smaller than the along-strike shear displacement. When the working face advanced beyond the surface test well from 0 m to 200 m, down-dip shear displacement is the most severe. The maximum shear displacement toward the headgate is 315 mm.

### 5 DISCUSSION

It is known to us that, with the advancement of working face, the movement of the overlying strata is complex. It is very difficult to grasp the overlying strata movement law, especially to quantify the characteristics of the overlying strata movement. Previous researchers mainly studied the stress distribution, subsidence, fracture distribution and shear displacement of the overlying strata under single seam mining. There are few studies on slice mining conditions. Especially, there is no relevant research report on shear displacement of the overlying strata under slice mining. When surface wells are arranged above the coal seam, the overlying strata movement under slice mining will cause repeated shear deformation of surface wells, which will lead to the failure of surface wells. To solve this problem, exploring the shear displacement of the overlying strata by slice mining is of great significance.

Based on the law of the ground and the overlying strata subsidence, the shear displacement of the overlying strata under the condition of semi-infinite seam mining and limited mining is analyzed. The calculation method of shear displacement at any point of the overlying strata is established. The two-dimensional physical simulation method is used to

| Variables in formula | The parameter values of depth 96.7 m | The parameter values of depth 192.01 m | The parameter values of depth 292.6 m |
|---------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| $H_1$                           | 3.15 m                            | 5.06 m                            | 4.49 m                            |
| $W_1$                           | 3.95 m                            | 4.30 m                            | 4.60 m                            |
| $W_0$                           | 0                                 | 0                                 | 0                                 |
| $r_{Y1}$                        | 46.04 m                           | 106.67 m                          | 172.11 m                          |
| $t_1$                           | 62 d                              | 62 d                              | 62 d                              |
| $C_1$                           | 0.64                              | 0.78                              | 0.94                              |
| $V_1$                           | 7 m/d                             | 7 m/d                             | 7 m/d                             |
| $l$                             | 891 m                             | 891 m                             | 891 m                             |

**TABLE 2** The parameter values of formula (5) in different depth
simulate the shear displacement law of the overlying strata under slice mining. The rationality of theoretical calculation is verified. In order to verify the correctness of theoretical analysis and simulation experiment, a test well was arranged in panel 4308 to monitor the shear displacement of the overlying strata. The above research work is innovative and has good application value.

With the advancement of working face, shear displacement mainly occurs to the right side of the test well (the advancing direction of the working face). When working face advances about 194 m, shear displacement returns to the vicinity of the well position. The law of shear displacement of the overlying strata in inclination is consistent with the physical simulation results. This shows that the shear displacement of the overlying strata is related to the location of surface wells.

Although the field test only monitors the shear movement of the upper seam, the physical simulation test provides guidance for the shear movement of the overlying strata after lower seam mining. Especially, it can provide guidance for the arrangement of CBM surface wells and shear stress of casing in mining area.
There are still some deficiencies in this study. In the future, we will look for a suitable working face and continuously monitor the shear movement characteristics of the overlying strata under slice mining. Three-dimensional physical simulation method will be used to study the shear displacement of the overlying strata.

### 6 | CONCLUSION

In order to analyze the shear displacement law of the overlying strata under slice mining, the calculation of shear displacement at any point on the interface of composite rock beam under slice mining is analyzed. Physical simulation was used to investigate the shear movement of the overlying strata by slice mining. Additionally, field test of shear movement of the overlying strata was implemented to verify the shear displacement of theoretical analysis. Major conclusions of this study are as follows:

- The shear displacement under slice mining is obtained by theoretical analysis. The shear displacement at any point on the interface of strata in composite rock beam under slice mining is analyzed. Physical simulation test results show that the shear movement of the overlying strata under slice mining mainly shows “increase → decrease →increase → decrease.” When the working face in upper seam advanced 1360 mm, the shear displacement of the overlying strata in the left side increases to the maximum value (about 12 mm). When the working face in lower seam advanced 340 mm, the shear displacement of the overlying strata in the left side increases to the maximum value (about 20 mm). The shear displacement curve of the overlying strata forms a “W” shape after slice mining. The maximum shear displacement of the overlying strata by the lower seam mining is 1.67 times of that of the overlying strata by the upper seam mining.

- The shear displacement of the overlying strata movement after mining has “time-delay” effect. The larger the depth of the measuring point is, the larger value of the along-strike shear displacement is. However, the breakage of the key strata of the overlying strata will cause the shear displacement of the overlying strata to increase rapidly. The farther the working face is from the surface test well, the smaller the shear displacement of the overlying strata is.

- Before the working face advances to the surface test well, there is a demarcation depth (127.98 m) in the shear displacement of the overlying strata. The shear displacement of the strata below the demarcation point is "S" shape (amplitude 50 mm). When the working face advanced to 34 m to 94 m beyond the test well, the overlying strata underwent severe shear displacement. When the working face advanced to 74 m away from the surface test well, the shear displacement of the overlying strata between 10# (depth of 192.01 m) and 16# (depth of 300.07 m) is larger than that at the upper position.

- The shear displacement of the overlying strata is coincident with the along-strike shear displacement, and the down-dip shear displacement is smaller than the along-strike shear displacement.

- It is of important theoretical value to guide the protection of coal mine shaft, the safety protection of shale gas, or coalbed methane surface wells under slice mining. However, there are still some aspects to be further studied, such as the distribution law of horizontal overlying strata stress and experimental study on shear displacement of the overlying strata at different down-dip positions under slice mining.

### ACKNOWLEDGMENTS

This study is supported by National Science and Technology major projects (2016ZX05045-001, 2016ZX05067-001), the National Natural Science Foundation of China (51874348), and Chongqing innovation leading talent support program (cstc-cxjlrc1911).

### CONFLICT OF INTEREST

The authors declare no conflict of interest, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed. Meanwhile, the founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

### AUTHOR CONTRIBUTIONS

Junhui Fu and Guangcai Wen conceived and designed the experiments; Xuelin Yang performed the experiments; Junhui Fu and Haitao Sun analyzed the data; and Junhui Fu and Haitao Sun wrote the paper.

### ORCID

Junhui Fu [https://orcid.org/0000-0002-2240-5143](https://orcid.org/0000-0002-2240-5143)

Xuelin Yang [https://orcid.org/0000-0003-2216-5052](https://orcid.org/0000-0003-2216-5052)

### REFERENCES

1. Yang X, Wen G, Dai L, Sun H, Li X. Ground subsidence and surface cracks evolution from shallow-buried close-distance multi-seam mining: a case study in Bulianta Coal Mine. *Rock Mech Rock Eng*. 2019;52(8):2835-2852.

2. Yin DW, Chen SJ, Liu XQ, et al. Effect of joint angle in coal on failure mechanical behavior of roof rock-coal combined body. *Q J Eng Geol Hydrogeol*. 2018;51(2):202-209.
3. Chen SJ, Yin DW, Jiang N, et al. Simulation study on effects of loading rate on uniaxial compression failure of composite rock-coal layer. Geomech Eng. 2019;17:333-342.

4. Xu T, Yang T, Chen C. Mining induced strata movement and roof behavior in underground coal mine. Geomech Eng. 2015;1:79-89.

5. Li Y. Analytical examination for the stability of a competent stratum and implications for longwall coal mining. Energy Sci Eng. 2019;7:469-477.

6. Bakun-Mazor D, Hatzor Y, Dershowitz W. Modeling mechanical layering effects on stability of underground openings in jointed sedimentary rocks. Int J Rock Mech Min Sci. 2009;46(2):262-271.

7. Ma WJ, Hu HF. The strata movement regularity and parameter simulation analysis in multiple seams repeated mining. Appl Mech Materials. 2013:295–298:2935-2939.

8. Ma L, Jin Z, Liang J, Sun H, Zhang D, Li P. Simulation of water resource loss in short-distance coal seams disturbed by repeated mining. Environ Earth Sci. 2015;74:5653-5662.

9. Wang DC, Yang YJ, Wang K, Zhao NN. Numerical simulation of study on rupture development rules of overburden strata in repeated mining. Adv Materials Res. 2012:433-440:1933-1939.

10. Xie J, Xu J, Wang F, Guo J, Liu D. Deformation effect of lateral roof roadway in close coal seams after repeated mining. Int J Min Sci Technol. 2014;24:597-601.

11. Tajduś K. Analysis of horizontal displacement distribution caused by single advancing longwall panel excavation. J Rock Mech Geotech Eng. 2015;7:395-403.

12. Tajduś K. Mining-induced surface horizontal displacement: the case of BW Prosper Haniel mine. Archive Min Sci. 2013;58(4):1037-1055.

13. Tajduś K. The nature of mining-induced horizontal displacement of surface on the example of several coal mines. Archive Min Sci. 2014;59(4):971-986.

14. Daigle LC, Mills K. Experience of monitoring shear movements in the overburden strata around longwall panels. Proceedings of the 17th Coal Operators’ Conference, Mining Engineering, University of Wollongong. 2017:125-137.

15. Daigle LC. Understanding fracture distribution within intrusive sills. The Cordeaux Crinanite a case example from the Illawarra Coal Measures in Proceedings 10th Australia New Zealand Conference on Geomechanics, Common Ground, Brisbane. 2007;12:480-485.

16. Mills KW, Garratt O, Blacka BG, Daigle LC, Rippon AC, Walker RJ. Measurement of shear movements in the overburden strata ahead of longwall mining. Int J Min Sci Tech. 2016;26:97-102.

17. Mills KW, Puller J. Measurements of horizontal shear movements ahead of longwall mining and implications for overburden behavior. Proceedings of the 34th International Conference on Ground Control in Mining, Morgantown, West Virginia. 2015;154-159.

18. Mills KW. Mechanics of horizontal movements associated with coal mine subsidence in sloping terrain deduced from field measurements. Proceedings of the 33rd International Conference on Ground Control in Mining, Morgantown, West Virginia. 2014;304-311.

19. Liu DY, Sun HT. A model of shear slipping of overlying strata under mining disturbance. Rock Soil Mech. 2010;31(2):609-614.

20. Sun HT, Hu QT, Zheng YR, et al. Method to gain the bed separation displacement of overlying strata and its application. Coal Sci Tech. 2011;39(1):16-19.

21. Liu YZ, Lu TK, Yu HY. Surface boreholes for drawing of gob gases and its stabilities analysis. Chin J Rock Mechan Eng. 2005;24(1):4982-4987.

22. Hu HF, Li M, Wang GR. Feature research of movement and deformation to surface of earth due to repeatedly mining. Adv Mat Res. 2012;402:784-789.

23. Li B, Liang Y, Zou Q. Determination of working resistance based on movement type of the first subordinate key stratum in a fully mechanized face with large mining height. Energy Sci Eng. 2019;7:777-778.

24. He GQ, Yang L, Ling GD. Mining Subsidence. China: China University of mining and Technology Press; 1991.

25. Liu JZ, Sun HT, Hu QT. Surface borehole synthesis tension deformation fracture time-space rule. Int J Min Sci Technol. 2012;22(4):447-602.

26. Sun HT, Lin FJ, Zhang J. Shear deformation failure model of surface drilling and its spatial regularity analysis. Min Safety Environ Protect. 2011;28(1):72-76.

27. Sun H-T, Zhao X-S, Li R-H, Jin H-W, Sun D. Emission reduction technology and application research of surface borehole methane drainage in coal mining-influenced region. Environmen Earth Sci. 2017;76(9):1-19.

28. Chen JH, Hu QT, Wu WB. Identification method for high-risk position of casing damage in the surface wellbore of a mining subsidence area based on laminate theory. Disaster Adv. 2013;12(6):139-148.

How to cite this article: Fu J, Wen G, Sun H, Yang X. Study on the shear movement law of overlying strata by slice mining. Energy Sci Eng. 2020;8:2335–2351. https://doi.org/10.1002/ese3.668