The influence of advance speed on overburden movement characteristics in longwall coal mining: insight from theoretical analysis and physical simulation

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Abstract
The advance speed of a longwall face is an essential factor affecting the mining pressure and overburden movement, and an effective approach for choosing a reasonable advance speed to realise coal mine safety and efficient production is needed. To clarify the influence of advance speed on the overburden movement law of a fully mechanised longwall face, a time-space subsidience model of overburden movement is established by the continuous medium analysis method. The movement law of overburden in terms of the advance speed is obtained, and mining stress characteristics at different advance speeds are reasonably explained. The theoretical results of this model are further verified by a physical simulation experiment. The results support the following conclusions. (i) With increasing advance speed of the longwall face, the first (periodic) rupture interval of the main roof and the key stratum increase, while the subsidience of the roof, the fracture angle and the rotation angle of the roof decrease. (ii) With increasing advance speed, the roof displacement range decreases gradually, and the influence range of the advance speed on the roof subsidience is 75 m behind the longwall face. (iii) An increase in the advance speed of the longwall face from 4.89 to 15.23 m/d (daily advancing of the longwall face) results in a 3.28% increase in the impact load caused by the sliding instability of the fractured rock of the main roof and a 5.79% decrease in the additional load caused by the rotation of the main roof, ultimately resulting in a 9.63% increase in the average dynamic load coefficient of the support. The roof subsidience model based on advance speed is proposed to provide theoretical support for rational mining design and mining-pressure-control early warning for a fully mechanised longwall face.

Keywords: advance speed, overburden movement, roof fall, physical model, longwall mining

1. Introduction
With the development of coal mining technology, the improvement in longwall face machinery, equipment manufac-

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become the main development directions for thick coal seam mining in China (Zhang et al. 2021). Compared with on-site geological conditions, such as mining depth and coal thickness, advance speed has high controllability and adjustability and thus has an important influence on the mining pressure, overburden movement and even dynamic disaster events (Guo et al. 2019). Figure 1 shows the statistical results of 30 high-intensity longwall faces of thick coal seams in China’s western mining area. It can be seen from the figure that many coal mines in the Shendong mining area have an advance speed of 20 m/d. Among the studied faces, 84% of the longwall face advance speeds were faster than 5 m/d and 40% of the longwall face advance speeds were considerably faster than 10 m/d. With the increase in longwall face advance speed, in the roof, the maximum principal stress loading rate increases gradually (Exadaktylos & Vardoulakis 2001) and the change in the loading rate consequently changes the tensile strength, compressive strength and modulus of elasticity of the rock (Koyama & Jing 2007; Kim & Changani 2016). Therefore, the increase in the longwall face’s advance speed affects the roof movement and failure law, and thus affects the longwall face pressure (Zhao et al. 2020).

Because the goaf contains a large amount of toxic and harmful gases, it is generally kept in a closed state to prevent the occurrence of mining disasters such as air leakage on the longwall face and spontaneous combustion of residual coal (Zhang & Zhang 2019; Zhang et al. 2020). The actual working resistance of the hydraulic support is usually used to invert overburden movement characteristics, while the instability form and subsidence characteristics of the main roof stratum are mostly qualitatively described (Majdi et al. 2012; Kong et al. 2019; Song et al. 2020). At present, the primary methods to study the advance speed on the main roof movement law of a fully mechanised mining face are physical simulation experiments and numerical simulations. Based on the physical simulation experiment and numerical simulation method, the research results of the overburden movement law of a fully mechanised mining face mainly include the following: (i) with an increase in longwall face advance speed, the peak abutment stress in the longwall face increases and the failure range of the rock around the longwall face decreases (Yang et al. 2015; Li et al. 2019). (ii) With an increase in advance speed in the longwall face, the amount of roof separation, the sliding range of the main roof joints and the rotating subsidence amount of the main roof stratum all decrease (Li et al. 2018), while the overburden subsidence velocity and the movement range of the main roof stratum increase (Wang et al. 2012). (iii) With an increase in longwall face advance speed, the ground movement deformation rate increases, the fracture angle increased linearly with the advance speed’s growth and the development period decreases linearly (Liu et al. 2019).

Due to its characteristics, a discrete element numerical simulation can monitor not only the deformation parameters such as the displacement, stress, and velocity of each block in model time, but also the instability form of the roof stratum in real time (Le et al. 2018, 2019). However, in the research process, the size and joint parameters of the block division in the discrete element numerical simulation process have a significant influence on the form and position of rock fracture instability. Simultaneously, there is no clear basis for the size of the block division, and joint parameter selection is difficult in engineering practice. Additionally, the results from numerical simulation are difficult to match to features observed during field engineering. Physical simulation experiments mainly focus on the influence of the longwall face advance speed of the main roof weighting interval and the roof subsidence characteristics (Kang et al. 2018). With the development of infrared thermal imaging technology, the analysis of the variation in thermal infrared radiation during fractured
coal-rock stratum failure during mining has been realised at this stage (Sun et al. 2017; Wei et al. 2019), and precursory information on rock rupture has been obtained by combining infrared thermal imaging technology with image processing technology (Ghabraie et al. 2015).

In addition to physical simulations and numerical simulations, many scholars have established theoretical models for predicting the roof stratum movement and fracture instability of longwall faces (Wang et al. 2017; Liang et al. 2019), including the voussoir beam model (Qian et al. 2010), analogous hyperbola subsidence model (Sun et al. 2019) and pressure arch model (Wang et al. 2018). Because the movement and failure process of overburden in stopes is an extremely complex mechanical process, current research models cannot reasonably explain the movement of the whole overburden and the influence of advance speed is rarely considered in such models.

Therefore, this paper uses a combination of theoretical analysis and physical simulation to establish a roof stratum movement model that considers the advance speed of the longwall face and quantitatively analyses the influence of advance speed on the roof stratum subsidence characteristics during longwall mining.

### 2. Engineering background

The study mine is located in Wanli town, approximately 7 km north of Ordos city, as shown in figure 2a. The mine is mainly mining the 5–1 coal seam, with an average thickness of 5.2 m and a dip angle of 0–3°. The 15 106 longwall face of the study mine adopts the fully mechanised mining method. The strike length is 2193 m, the inclined length is 300 m and the mining height is 5.2 m. The overburden is 80–120 m thick and the unconsolidated layer is 0–5 m thick. The immediate roof and main roofs are 9.9-m-thick sandy mudstone and 7.0-m-thick fine sandstone, respectively. According to the key stratum calculation, the key stratum is a 12.0-m-thick coarse sandstone, as shown in figure 2b in the stratigraphic column.

### 3. Subsidence velocity model of longwall face roof stratum

In the process of longwall mining, the movement of the overburden is closely related to the longwall face, and the advance speed influences the movement of the overburden. The subsidence velocity of any point in the overburden undergoes a process of gradually increasing from zero and then decreasing to zero. The curve of the vertical displacement of the roof stratum of the longwall face with time can be expressed as an ‘S’-shaped curve. Because a logistic equation approximately satisfies the velocity equation of points in the roof stratum $S'(t)$ (Luo & Peng 2000), a differential equation is obtained:

\[
\begin{align*}
S_f &= \frac{S(t)}{S_0(x_a)} \\
S_{pf} &= \frac{S_0(x_a) - S(t)}{S_0(x_a)} .
\end{align*}
\] (1)

In this equation, $S(t)$ is the subsidence at the measuring point on line P (figure 3) at time $t$, $S_f$ is the ratio the current subsidence to the maximum subsidence, $S_{pf}$ is the ratio of the potential subsidence to the maximum subsidence, $S_0$ is the ratio of the potential subsidence to the maximum subsidence, $S_0(x_a)$ is the final subsidence at the measuring point and $x_a$ is the horizontal distance between the measuring point and
the longwall face. Since the increase in vertical displacement of a point in the roof stratum is proportional not only to the potential subsidence coefficient $S_{pf}$ but also to the current settlement coefficient $S_{f}$ of the point, the following differential equation is established:

$$S'_{f}(t) = \frac{\partial S(t)}{\partial t} = c S_{pf} S_{f}.$$  \hspace{1cm} (2)

In this equation, $S'_{f}(t)$ is the subsidence rate of the measuring point at time $t$, and $c$ is the subsidence velocity coefficient, $c = H \sqrt{\frac{\gamma_{i} E_{i}}{\sigma_{ti} \mu_{i} \gamma_{i} E_{i}}}$ (Li 2004), $H$ is the burial depth of the stratum, $\gamma_{i}$ is the density of the $i$-th roof, $E_{i}$ is the elastic modulus of the roof, $\sigma_{ti}$ is the uniaxial tensile strength of the $i$-th roof and $\mu_{i}$ is the uniaxial tensile strength of the poisson ratio $i$-th roof.

By combining equation (1) with equation (2), the subsidence rate of the measuring point at time $t$ is given by:

$$S'_{f}(t) = \frac{dS(t)}{dt} = c S_{0}(x_{n}) S_{f}(x_{n}) + \left[ 1 - S_{f}(x_{n}) \right]. \hspace{1cm} (3)$$

By integrating the variables in equation (3), the subsidence value of the measuring point at time $t$ can be obtained:

$$S(t) = S_{0}(x_{n}) \left[ 1 + \frac{S_{0}(x_{n}) - s_{0}}{s_{0}} e^{-\frac{a t}{s_{0}(x_{n})}} \right]. \hspace{1cm} (4)$$

In this equation, $s_{0}$ is the initial vertical subsidence.

$$S_{0}(x_{n}) = (1 + K h) \left[ S(x_{n} - d_{0}) - S(x_{n} - (L - d_{0})) \right]. \hspace{1cm} (5)$$

In this equation, $d_{0}$ is the inflection point offset distance, $K$ is the rock subsidence factor, $K = 0.29235 \left( \frac{H - \delta}{M} \right)^{0.0546}$ (Guo et al. 2003), $\delta$ is the thickness of unconsolidated layer and $M$ is the mining height.

$$L = Vt. \hspace{1cm} (6)$$

In this equation, $L$ is the face advance distance and $V$ is the advance speed of the longwall face.

By combining equations (4), (5) and (6), we can obtain:

$$S(t) = S_{0}(x_{n}) \left[ 1 + \frac{S_{0}(x_{n}) - s_{0}}{s_{0}} e^{-\frac{a t}{s_{0}(x_{n})}} \right],$$

$$S_{0}(x_{n}) = (1 + K) \left[ S(x_{n} - d_{0}) - S(x_{n} - (L - d_{0})) \right],$$

$$S(x) = \frac{S_{max}}{2} \left( 2 \sqrt{\pi} \int_{0}^{\sqrt{x}} e^{-\lambda^{2}} d\lambda + 1 \right).$$  \hspace{1cm} (7)

When the geological conditions are determined, the burial depth and the inflection point offset distance are constant. The time-varying curves of the roof subsidence of the longwall face at different advance speeds are shown in figure 4. With increasing advance speed, the instantaneous subsidence velocity of the roof stratum increases greatly, leading to an increase in the dynamic load of the longwall face.

4. The physical simulation

The dimensions of the physical simulation experimental platform are length $\times$ width $\times$ height $= 1.8 \times 0.2 \times 1.6$ m. The model is established according to the geological conditions of the mine. The coal floor’s distance to the surface is 116.5 m and the simulation range is the rock from the coal
floor to the surface. The vertical stress gradient is 2.5 MPa per 100 m, while the horizontal stress is determined by the boundary conditions. The geometric similarity ratio of the model is $C_L = 1:100$, the bulk density similarity ratios were $C_\gamma = 1:1.76$ (rock) and $C_\gamma = 1:1$ (coal). According to simulation theory, the parameters of the simulation model and the geology archetype have the following relationship:

$$C_\sigma = C_\gamma C_L = 52.8,$$ (8)

where $C_\sigma$ is the similarity ratio of stress, $C_\gamma$ is the similarity ratio of the volumetric weight and $C_L$ is the geometry similarity ratio.

The similarity ratio of the time is

$$C_t = C_{1/2}^L = 10.$$ (9)

To obtain the appropriate compressive strength of the similar simulation material, large-scale mechanics tests were conducted on the prepared samples and the appropriate ratios of similar simulated materials were obtained (Kang et al. 2007), as shown in Table 1 (Ju et al. 2017; Zhang et al. 2019).

Due to the influence of equipment debugging and roof pressure prevention in the initial stage of longwall mining, the average advance speed of the longwall face is 4.89 m/d. As the

| Lithology            | Thickness (cm) | Tensile strength (MPa) | Elastic modulus (GPa) | Cohesion (MPa) | Poisson | Compressive strength (MPa) | Bulk density (kg m$^{-3}$) | Ratio (sand: lime: gypsum) |
|----------------------|----------------|------------------------|-----------------------|----------------|---------|---------------------------|-----------------------------|----------------------------|
| Unconsolidated layers| 4.5            | 4                      | 4                     | 0.3            | 3.0     | 2290                      | 1300                        | 8:8:2                      |
| Fine sandstone       | 11.2           | 5.97                   | 9.54                  | 3.5            | 0.17    | 36.82                     | 2550                       | 6:5:5                      |
| Sand mudstone        | 18.4           | 3.03                   | 12.12                 | 3.62           | 0.18    | 25.48                     | 2480                       | 7:5:5                      |
| Medium sandstone     | 5.5            | 2.9                    | 9.43                  | 3.56           | 0.18    | 43.40                     | 2530                       | 6:5:5                      |
| Sand mudstone        | 12             | 4.89                   | 10.32                 | 4.12           | 0.23    | 41.22                     | 2640                       | 6:5:5                      |
| Siltstone            | 5.5            | 2.9                    | 9.43                  | 3.56           | 0.18    | 43.40                     | 2530                       | 8:6:4                      |
| Coarse sandstone     | 10.4           | 2.53                   | 9.54                  | 3.5            | 0.17    | 30.41                     | 2480                       | 7:5:5                      |
| Siltstone            | 7              | 3.89                   | 10.56                 | 4.32           | 0.17    | 42.35                     | 2550                       | 6:5:5                      |
| Sand mudstone        | 4.4            | 4.14                   | 8.95                  | 2.87           | 0.20    | 31.22                     | 2480                       | 7:5:5                      |
| Fine sandstone       | 4.5            | 3.08                   | 2.56                  | 2.13           | 0.18    | 23.21                     | 2530                       | 8:6:4                      |
| Mudstone             | 5.2            | 0.75                   | 1.68                  | 1.63           | 0.33    | 8.15                      | 1430                       | 8:7:3                      |
| 5–1 coal             | 5              | 4.55                   | 7.18                  | 4.23           | 0.18    | 56.37                     | 2530                       | 6:5:5                      |
face advances over 130 m, the equipment commissioning is regular and the average advance speed is 15 m/d. Therefore, the tested advance speeds of the similar simulated longwall face in this paper are chosen as 5 m/d (model A) and 15 m/d (model B). There are generally two ways to change the advance speed of the longwall face: one is to advance different distances within the same time; the other is to advance the same distance over different times. The first method is easier to implement and more in line with the actual situation of the study site. The time similarity ratio is the ratio of the amount of time consumed by the model to that by the geological prototype. Roof stratum movement caused by advancement in the longwall face and the length and interval of mining time will affect the roof movement law. Therefore, the time similarity ratio is used to determine the amount of time required for a physical model. The research mine adopts a 4/6 working system, including three working time periods for coal mining and one for maintenance. The best way to control the advance speed is beyond the scope of this paper. According to the time similarity ratio ($C_t = 1:10$) and geometric similarity ratio ($C_L = 1:100$), the advance speed of the longwall face is controlled by advancing distances within the same time. Specifically, models A and B advance 1.66 and 5 cm for each working time period (0.6 hours), respectively. Three excavations were carried out in one day, i.e. 5 and 15 cm of excavation is achieved in 2.4 hours.

At the same time, two similar models with the same parameters of models A and B are created. The main roof (fine sandstone) and key stratum (coarse sandstone) are painted with white water-based color pigment, and a mining contrast test of the longwall face under different advance speeds is carried out. In the model, a boundary coal pillar of 20 m (the following model sizes are converted from the actual sizes) is set at the starting line and the ending line, and the excavation distance is 140 m. A total of one vertical measuring line (line P) and six horizontal measuring lines (lines I–VI) are established, as shown in figure 4. An industrial camera measuring system monitors the overburden movement data.

5. Results and analysis

5.1. The roof stratum failure characteristics

Figure 5 shows the evolution process of the roof stratum failure of model A with longwall face advancement. When the longwall face advances to 40 m (figure 5a), part of the immediate roof caves due to bending and tensile failure. The other part of the immediate roof undergoes bending deformation, and its caving height is 8.7 m. The progressive movement of the overburden showed that the main roof bridged over a long distance of face advance and then ruptured at a face advance of 65 m (figure 5b). The roof stratum fracture angle on one side of the longwall face is $56^\circ$, the side of the open-off...
Figure 6. Roof failure evolution process of model B as the longwall face advances.

cut is 63°, the main roof rotation angle is 8.6° and the caving height of the rock increases to 24.7 m. As the longwall face continues to advance, the roof stratum fracturing-induced instability gradually develops upward. When the longwall face advances to 100 m, the key stratum ruptures for the first time: the first rupture interval is 100 m and the caving height is 63.2 m. The fracture angle is 62° on one side of the longwall face, that on the side of the open-off cut is 65° and the main roof rotation angle is 8.0°. Figure 5d shows the roof of the longwall face’s final failure pattern when model A is advanced to the ending line. In this process, the main roof experiences seven periodic ruptures with rupture intervals of 10–12.5 m.

Figure 6 shows the evolution process of the roof stratum failure of model B with longwall face advancement. When the longwall face advances to 45 m, the immediate roof caves completely (figure 6a), the caving height is 9.9 m and bending deformation of the main roof occurs. As the face advances over 75 m, the main roof caves for the first time, the first rupture interval reaches 75 m and the caving height of the rock increases to 24.7 m. The fracture angle on one side of the longwall face is 56°, that on the side of the open-off cut is 60° and the main roof rotation angle is 6.1°. When the longwall face advances to 120 m, the key stratum ruptures for the first time: the first rupture interval is 120 m and the caving height is 89.8 m. The fracture angle on one side of the longwall face is 60°, that on the side of the open-off cut is 64° and the main roof rotation angle is 6.5°. Figure 6d shows that the main roof experienced four periodic failures when the longwall face was advanced to the ending line and the periodic rupture interval was 17.5–22.5 m.

The comparison between the failure characteristics of the roof stratum is shown in figures 5 and 6, along with the increase in advance speed, the fracture angle of model A that is 2° to 3° larger than that of model B and the rotation angle of model A that is 1.5° to 2.5° larger than that of model B. The comparison between figure 5d and 6d shows that the first and periodic rupture intervals of the main roof are increased by 10 m, and the first and periodic rupture intervals of the key stratum are increased by 20 and 10 m, respectively. The results show that the increase in the advance speed of the longwall face leads to a short overhanging roof stratum duration and incomplete roof movement, resulting in a reduction in the roof fracture angle. The increase in the advance speed of the longwall face causes an increase in the loading rate of the roof stratum, and the tensile strength of the rock shows prominent pseudo enhancement characteristics with an increase in the loading rate (Yang & Yu 2017). Therefore, with the increase in the advance speed of the longwall face, the mechanical properties of the roof stratum increase, resulting in a decrease in the roof rotation angle and an increase in the main roof (the key stratum) rupture interval.
5.2. Roof movement characteristics

Figure 7 shows six subsidence survey lines (I–VI) in models A and B when the longwall face advances to 140 m. Among them, the subsidence curves of survey line I in models A and B are the same, which indicates that the change in advance speed has no apparent effect on the immediate roof. The subsidence curves of lines II–VI in models A and B are obviously different. The subsidence range of line II in model A is more extensive than that in model B, and the maximum subsidence of line II in model A is only 3937 mm. Compared with that in model B, the maximum subsidence is model A is 3.3% smaller. This shows that the increase in the advance speed of the longwall face leads to a decrease in the bulking coefficient of the caving rock block, resulting in more subsidence space for the main roof. With increasing advance speed, the subsidence range of lines IV–VI is the same as that of line II, while the maximum subsidence results of lines IV–VI observed in model A are 3784, 3533 and 3049 mm, respectively. Compared with the results of model B, the maximum subsidence results of model A are 3.3, 4.4 and 14.9% greater, respectively. This shows that under rapid advance, the movement time of the roof stratum is reduced, which leads to a reduction in the roof stratum movement range and that the maximum subsidence of the rock above the key stratum decreases with decreasing burial depth because the caving blocks under the key stratum are not fully compacted.

Figure 8 shows the change in the subsidence along the P survey line in models A and B when the longwall face advances to the ending line. When the advancing distance of the longwall face is behind survey line P, the subsidence data of survey line P are 0 mm. When the advancing distance of the longwall face is 15–30 m ahead of the P survey line, the subsidence curves in models A and B show an obvious ‘bifurcation’ phenomenon between measuring points P_2–P_4, while the subsidence curves remain parallel between measuring points P_5–P_11. In this stage, due to the control of the key stratum, the influence of the advance speed on the roof movement characteristics is mainly concentrated on the underlying stratum of the key stratum. When the advancing distance of the longwall face is 45–60 m ahead of the P line, the subsidence curves in models A and B are ‘bifurcated’ between measuring points P_4–P_11. The results show that the roof stratum of model A is under fully rotary subsidence. However, the increase in the rupture interval and the insufficient movement of the key stratum in model B lead to a decrease in its rotation angle, which slows the bending and subsidence of the upper stratum, resulting in the ‘bifurcation’ of the curve. At this stage, the impact of the advance speed on the movement characteristics of the roof is mainly concentrated on the upper stratum of the key stratum. When the advancing distance of the longwall face is 75 m ahead of the P line, the subsidence curves of this line are consistent between models A and B (Jiránková 2012). Therefore, the results indicate that the influence range of advance speed on roof subsidence along the P survey line is 75 m ahead of the longwall face.

To study the influence of the longwall face advance speed on the main roof subsidence velocity, measuring point P_2 on survey line P (as shown in figure 4) was selected to analyse the subsidence and subsidence velocities of models A and B. Figure 9 shows the curve of the subsidence and subsidence velocities at measuring point P_2 under the two advance
The subsidence of measuring point P2 in model A is more significant than that in model B. As the longwall face advanced from the open-off cut to the ending line, the subsidence velocity of model B at measurement point P2 experienced two peaks of 1861 and 929 mm/d (daily subsidence of the roof stratum), and the peak values of model A were smaller than those of model B. Because the main roof and the key stratum control the roof stratum, when the main roof (or key stratum) reaches its limit span, the roof stratum will fracture and the fractured rock blocks will form a hinged structure. With the increase in the advance speed of the longwall face, the bending subsidence of the roof stratum is incomplete and the bulking coefficient of the immediate roof is small, which leads to an increase in the separation between the main roof and the immediate roof and ultimately increases the subsidence velocity of the P2 measuring point when the hinged structure becomes unstable. The first three peaks in model A and the first peak in model B are caused by the initial fracture of the main roof, while the fracture instability of the key stratum leads to the formation of the fourth peak in model A and the second peak in model B.
The horizontal distance between the measuring point on survey line P and the bulking cut is 60 m. The subsidence velocity coefficient is 3.0, the rock subsidence factor is 1/150 and the initial subsidence is 100 mm. The subsidence of the six measuring points of models A and B on survey line P varies with face advance, as shown in figure 10. A comparison of the theoretical calculation value of different advance speeds with the physical simulation results shows that the settlement calculation formula proposed in this paper is compatible with the physical simulation monitoring results. Therefore, this theoretical model can accurately describe the roof movement law of the longwall face.

6. Field measurements

The pressure conditions of supports #25, #70 and #110 in two stages with a large difference in advance speeds were selected for comparison to verify the theoretical analysis against the physical simulation results, as shown in figure 11 and Table 2. The average advance speeds of the two stages are 4.89 and 15.23 m/d, respectively.

Figure 11 shows the changes in the working resistance and dynamic load coefficient of supports #25, #70 and #110 at different advance speeds. The total load of the support mainly includes the release pressure of the immediate roof, the impact load caused by the sliding instability of the main roof, and the additional load caused by the rotation of the main roof (Qian et al. 2010). When the advance speed of the longwall face increased from 4.89 to 15.23 m/d, the load of the three supports increased from 6892.48 to 7097.99 kN, 7097.12 to 7341.48 kN and 6750.57 to 6980.50 kN, respectively. Compared with that of the advance speed of 4.89 m/d, the load of the three supports during the weighting period increased by 2.98, 3.44 and 3.40%, while the load of the three supports during the nonweighting period decreased by 5.72, 4.94 and 6.72%, respectively. The support’s dynamic load coefficient increased by 9.23, 8.82 and 10.85%, respectively, as shown in Table 2. Thus, when the advance speed of the longwall face increased from 4.89 to 15.23 m/d, the subsidence of the main roof decreased, resulting in a gradual decrease in the rotation angle, which lead to the reduction in the additional load generated by the rotation of the fracture rock block on the main roof. The final result was that the average load of the support decreased by 5.79% during the nonweighting period. With the increase in the advance speed, the amount of separation between the main roof and the immediate roof gradually increased, causing the subsidence velocity of the fracture block to increase; consequently, an increase in the impact load of the fracture block by 3.28% occurred due to sliding and instability. Finally, the average dynamic load coefficient of the support increased by 9.63%. The results of the physical simulation and theoretical analysis can effectively explain the
field-measured results, and the reasonable selection of long-wall face advance speed ensures safe mining of longwall faces.

7. Discussion

The advance speed of a longwall face is an essential factor affecting the mining pressure and overburden movement (Ghabraie et al. 2017), and an effective approach for choosing a reasonable advance speed to realise coal mine safety and efficient production is needed. Previous studies have shown that the final subsidence value of a surface measuring points is related to mining height, buried depth and other geological conditions, but has nothing to do with the advance speed. The advance speed has an impact on the overburden movement during the mining process, and the overburden movement reacts on the mining stress of longwall face. Hu et al. (2015) established the Knothe time-function model based on the general law of surface deformation. This model can be used to predict surface subsidence. However, the influence of advancing speed on surface subsidence cannot be further analysed by this model. On this basis, this paper uses the continuous medium analysis method to establish the overburden movement model, which describes the influence of different advance speeds on the subsidence characteristics of roof during mining. By assigning the model parameters $K$ and $c$, the quantitative analysis of roof subsidence caused by the advance speed under different geological conditions is realised. Figure 12 demonstrates that the prediction accuracy of improved logistic time-function model is significantly better than the Knothe time-function model (Zhang et al. 2020). The predicted results were consistent with the physical simulation monitoring data. Moreover, our model can accurately describe the three stages of strata migration: slow subsidence stage, rapid subsidence stage and stable subsidence stage (figure 12). However, the model adopted in this paper is based on continuous medium analysis and the influence of discontinuous joints of the roof is not considered (Cai et al. 2020). The roof model established in this paper is only tested under one geological condition. Subsequent tests should be conducted under multiple geological conditions to optimise the selection of parameters $K$ and $c$.

8. Conclusion

In this paper, a roof subsidence model based on longwall face advance speed is established, the influence of advance speed on roof movement law is studied through physical simulation and the reliability of the theoretical model is verified. Finally,
the theoretical model and physical simulation results are used to explain the internal mechanism of the mining pressure evolution characteristics. Based on the physical and theoretical analyses, we draw the following conclusions:

(1) Based on a logistic equation, a new model was established to describe the influence of different advance speeds on the subsidence characteristics of the roof stratum in the mining process, and then the quantitative analysis of the advance speed of the longwall face on roof subsidence was realised. The subsidence curves of six measuring points in the roof with different advance speeds in a physical simulation experiment were predicted and analysed by using the theoretical model. The physical simulation results are consistent with the predicted results of the theoretical model, which verifies the rationality of the roof subsidence model based on the advance speed. However, in the process of theoretical calculation, inaccurate range values for the determination of the subsidence velocity coefficient C were still found. Subsequently, sensitivity analysis of C and factors such as the burial depth, mechanical properties and stress of the rock should be established to obtain specific quantitative formulas.

(2) Through the physical simulation experiments, it was determined that the subsidence amount of the overburden, the rotation angle of the roof and the roof displacement range decrease with increasing advance speed, while the first (periodic) rupture intervals of the main roof and the key stratum increase. The influence range of the advance speed on the roof subsidence is 75 m behind the longwall face.

(3) Based on the physical simulation results and theoretical analysis, the field measurement results of the support load are explained and analysed. The advance speed of the longwall face increased from 4.89 to 15.23 m/d, resulting in a 3.28% increase in the impact load due to the sliding instability of fractured rock in the main roof. However, with increasing advance speed, the additional load caused by the rotation of the fracture block decreased by 5.79%. Finally, the average dynamic load coefficient of the support increased by 9.63%.

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