Evaluation of the face advance rate on ground control in the open face area associated with mining operations in Western China

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Abstract
The modern longwall faces in coal bases in Western China are being mined at an increasingly faster rate, yet the consequences of the face advance rate on the ground control and strata movement require further investigation. In this study, two improved physical models with different advance rates are developed to evaluate the roof failure characteristics; the strata movement; the displacement of the strong, massive roof; and the roof movement velocity. The results show that: (i) regular falls of the immediate roof and major falls of the hard roof are observed with the progressive development of the longwall face. Massive fractures on the roof strata extending from the face to the ground surface develop on a major roof fall. (ii) Model I, which has a slower face advance rate, shows a major roof fall interval of 65 m, which is slightly less than the 70 m found by Model II, which advances at a faster rate. Larger strata fractures are observed in Model I, while the gob area of Model II is better filled with waste rock materials. (iii) The displacement and velocity of the hard roof are unnoticeable until a massive roof fall. Maximum displacement occurs on a major roof fall, which is 50 mm for Model I and 30 mm for Model II. The maximum roof movement velocity on a major roof fall is 4.6 cm per min and 5.9 cm per min for Models I and II, respectively.

Keywords: face advance rate, ground control, major roof fall, physical model, strata movement

1. Introduction
Expecting to adjust to a more scientific and sustainable pattern of domestic coal production and consumption growth, China began production-optimizing and overcapacity-cutting operations in 2012 (Liu & Luan 2015; BP 2017; Cheng et al. 2019). As a result, 14 major coal bases with annual productions over 100 million tons were identified, which contribute to over 95% of the total coal production. Of those, the Shendong, Shanbei, Huanglong and Xinjiang coal bases are located in the north and west parts of China, where 6–9-m thick coal seams are widely found. Such seams are typically flat and shallow, above which massive and strong conglomerate channels exist. The high-seam single-pass longwall method is adopted for extracting the thick coal seams. By 2017, the maximum cutting height at Shangwan coal mine had reached almost 9 m. When extracting these coal seams, however, severer ground control problems were frequently observed both in the mining stope and on the ground surface in the form of longwall face collapses, roof falls at the faceline, aggressive weightings and the sudden dynamic loading on shields, leading to an iron-bound shield at the full closure of the hydraulic legs (figure 1) (Trueman et al. 2005; Xu et al. 2014; Wang & Cheng 2016; Song et al. 2017; Song & Chugh 2018; Kong et al. 2019). Massive ground cracks with an interval similar to the periodic roof weightings and the surface subsidence in a step function...
Figure 1. Ground control problems observed in the mining stope and ground surface: (a) a schematic of ground control problems; (b) iron-bound shield caused by major roof fall and (c) massive ground cracks.

may also occur (Fan et al. 2017; Chen & Hu 2018; Liu & Cheng 2019). These ground control problems may cause a loss of operating time, damage to the longwall shields, reduced production and profits, increased risk of water table contamination and negative impacts on the environment and ecology.

Factors affecting ground control problems can be identified as geological factors, shield capacity and technical factors (Prusek et al. 2017). Geological factors are listed as the depth of cover, presence of faults, seam inclination, mechanical parameters, thickness of the coal and roof etc. These factors are independent of the mine operators. In contrast, the shield capacity includes the setting load, yielding load, shield size, web width and tip-to-face distance and is dependent on operators. Efforts have been made to increase the shield capacity since the introduction of longwall shields. The current most powerful longwall shield in China has increased the cylinder diameter to 600 mm and the support load to 2600 t. Increasing the shield capacity benefits the face stability and ground control, but the technical improvement requires years of effort and great capital investment. Technical factors, on the other hand, include the mining methods, face length and width, previous extraction adjacent to the current longwall panel and the face advance rate, which are partially dependent on the mine operators and are considered more practical for enhancing the ground control in the mining stope. Of those, the face advance rate has potential positive impacts on the ground control since the face is moved to the next cycle before the occurrence of unacceptable roof-to-floor deflection (Wang et al. 2012; Guo & Wang 2017). A fast face advance rate is pursued by coal mines at the abovementioned coal bases, and modern longwall faces advance over 20 m/d (Guo et al. 2018). However, negative consequences, such as dynamic loading events on the shields, have also been observed. Further studies are required to understand the response of the ground movement and the pressure distribution at different face advance rates.

As mentioned above, both positive and negative impacts of the face advance rate have been documented in previous literature. A fast face advance rate is preferred because it not only improves the production and productivity but also improves the ground stability by reducing the roof-to-floor deflection (Hussein et al. 2013; Guo et al. 2018). It also reduces the risks of water inrush and sand bursting into the open face area during periodic weightings (Jia et al. 2015). Pressures on the cylinders of shields are relieved at an increased face advance rate from field observation (Liu 2010). Other benefits, such as reducing the volume of the mine water in the bed separation space, improved integrity of the roof, an increased periodic weighting interval, less extension of failure in the surrounding rocks and a decreased level of abutment pressure are also identified (Wang et al. 2012; Qiao et al. 2014).

Reverse outcomes are mostly observed as dynamic impact loading hazards (Qian & Shi 2010; Sdvyzhkov & Renata 2016). The frequent and intensive microseismic events in the overburden are considered to be closely related to high face advance rate (Liu & Li 2010; Zhang et al. 2017). The main roof typically caves in at a larger kinetic energy and shields are observed with slightly more severe impact loads during roof weightings (Wang & Wang 2015; Yang et al. 2017). The face advance rate increases the rate of ground surface subsidence and the duration of periodic weightings (Guo & Wang 2017). The risks of coal and gas burst hazards are also increased at methane rich seams (Wang & Xie 2010).

In addition, contradictory results were occasionally found regarding the impacts of the face advance rate on the ground control. Liu et al. and Li et al. observed less microseismic events at a faster face advance rate (Li et al. 2017; Liu et al. 2017). They analysed that a smaller face advance rate enables full extension of the rock failure into overburden and therefore more microseismic events. This does not agree with observations by other researchers (Liu & Li 2010; Zhang et al. 2017). Other evidence is given by US coal mines adopting faster face advance rates, while Germans have considered a slower mining rate both for producing less time-dependent surface deformations and protecting the surface structures (Luo et al. 2001). This discrepancy is mainly caused by different geological conditions where the coal beds occur.
Physical modelling of roof caving behaviours has been extensively performed to reproduce the progressive development of strata movement and roof failures (Song & Yang 2015). The models have considered the impact loading on shields (Yang et al. 2017), face failure and shield-strata interactions (Song et al. 2018, 2019; Yang et al. 2019), acoustic emission signals (Li et al. 2015) etc. However, the face advance rate was not included in previous models. Most of the physical models only reproduce the breakage of the hard roof behind the faceline, while roof failures ahead of or along the faceline are not uncommon in the abovementioned coal bases.

This paper attempts to study the face advance rate from physical models, and has three main goals: (i) incorporate the time similarity and realistic overburden loading conditions in the construction of physical models; (ii) obtain progressive development of roof failures and strata movement at different face advance rates; and (iii) assess the impacts of the face advance rate by analysing the vertical displacement of the main roof and roof movement velocity.

### 2. Physical modelling

#### 2.1. Model improvement

Very few physical models have included the face advance rate because it is difficult to observe its effect from a reduced-scale physical model. Changes must be made in the physical model to highlight the impact of the face advance rate. The following improvements are made in this work.

1. A uniformly distributed load is applied to the strata on the top of the model using a set of hydraulic rams to provide an additional vertical pressure. This is because the immediate and main roof in the physical model cannot cave in with a regular interval at its own weight.

2. Proper geo-mechanical modelling materials are carefully selected to construct the physical model (see Table 1 below). Cement is added to the mixture of physical materials to increase the strength and stiffness of the physical roof strata so that they fail and fall similar to the real case.

### Table 1. Proportion of the physical materials in terms of weight

| Lithology in the model | Percentage of the solid materials by weight | Percentage of the water over solid materials by weight |
|------------------------|-------------------------------------------|-------------------------------------------------------|
| Sand                   | 85.11%                                    | 4.26%                                                 |
| Gypsum                 | 6.38%                                     | 4.26%                                                 |
| Lime                   | 4.26%                                     | 4.26%                                                 |
| Cement                 | 10%                                       | 10%                                                   |
| Mudstone               | 85.11%                                    | 6.38%                                                 |
| Fine sandstone 1       | 80.00%                                    | 6.67%                                                 |
| Medium sandstone       | 82.36%                                    | 5.88%                                                 |
| Coal                   | 88.89%                                    | 7.78%                                                 |
| Fine sandstone 2       | 85.71%                                    | 7.14%                                                 |

### Table 2. Lithological sequence and thickness of the physical model

| Stratum No. | Lithology         | Bed thickness in the model (cm) | Bed thickness in the field (m) |
|-------------|-------------------|---------------------------------|-------------------------------|
| 10          | Mudstone          | 10.0                            | 10.0                          |
| 9           | Fine sandstone 1  | 13.0                            | 13.0                          |
| 8           | Mudstone          | 4.0                             | 4.0                           |
| 7           | Medium sandstone  | 13.0                            | 13.0                          |
| 6           | Mudstone          | 8.0                             | 8.0                           |
| 5           | Fine sandstone 1  | 13.0                            | 13.0                          |
|             | (strong and massive roof) |                   |                               |
| 4           | Mudstone          | 8.0                             | 8.0                           |
| 3           | Coal              | 5.0                             | 5.0                           |
| 2           | Fine sandstone 2  | 2.0                             | 2.0                           |
| 1           | Fine sandstone 2  | 6.0                             | 6.0                           |

3. The face advance rate is chosen by considering two patterns of face excavation rate modelling. One of them involves creating a same face advance distance for two models within different time periods. The other remains advancing the face at a different length within the same time. The second approach is used in this study due to its easy implementation and operation. Two of the constructed physical models are mined at 5 and 10 cm interval at every 5 minutes, respectively, i.e. 1 cm per min and 2 cm per min.

4. The time similarity is considered when performing the physical excavation modelling and data analysis. Note that the geometric similarity coefficient is 100:1 and the time similarity coefficient is 10:1. Therefore, 5 cm of face advance per 5 minutes in the physical model, which represents approximately 30 m per day in the field. This is slightly larger than that of the high-intensity mining operations in coal mines in Western China. Considering that the impacts of the face advance rates on ground control are difficult to reproduce in a small-scaled model, it is not unreasonable maintaining a higher advance rate in the modelling test.

#### 2.2. Physical modelling rig

Table 1 gives the proportion of each physical material selected in this work in terms of weight. Table 2 lists the...
2. Lithology and physical modelling rig

The physical modelling rig is 180 cm long, 20 cm wide and 100 cm high. The overall dimensions of the built model are 180 cm long, 20 cm wide and 82 cm high, as shown in figure 2. Note that the geometric similarity is 100:1 in this work. The 82-cm thick physical model therefore simulates an 82-m thick strata in the real case.

2.2. Loading conditions and modelling procedure

The physical model has roller boundaries along the right side and at the bottom. The left side is free by creating a vertical thin cut before coal excavation (figure 2). This is because if coal barriers are left at both sides of the model, the critical and supercritical widths in the physical model cannot be formed with the progressive development of the mine working, nor can the realistic angle of draw be observed. Extraction of the coal starts from the thin cut at the left boundary and advances 130 cm to the coal barrier at the right side. The free fall of the overburden behind the face following coal extraction is allowed since the confinement of the abutment at the left boundary is removed. The physical model only simulates a total of 69-cm strata resting above the seam; therefore, the roof hardly caves in by its own weight. A compensating pressure equivalent to the mining depth of the study mine site is provided by placing hydraulic rams on a steel plate on top of the model to create a uniform vertical pressure.

The measuring points (small pins) are placed on the roof strata with 10 cm intervals in width and height (figure 3). The 15 pin points beneath the main roof are denoted as P₁ to P₁₅ to record the displacement of the main roof. Movement of these points is measured by a charge-coupled device camera before and during extraction. The camera measuring system yields more accurate strata movement results than the traditional electronic theodolite. Two models are developed in this research (Models I and II) and advance at a 5- and 10-cm intervals every 5 minutes, respectively. They assess the influence of the face advance rate on the ground movement, strata failure, roof displacement and movement velocity. The vertical thin cut, compensating pressure and placement of the measurements are equivalent for both models.

3. Results and analysis

3.1. Roof failure and strata movement

Model I (1 cm per min). The progressive development of the roof failure and strata movement for Model I at 1 cm per min of the face advance is given in figure 4. The immediate roof caves in as the face advances 30 cm from the left boundary (figure 4a). The length of the overhanging immediate roof then increases with the development of the mine working (figure 4b). Roof failure extends upward and forward as the face advances 60 cm from the start position, with loose rock wastes regularly placed in the gob area (figure 4c). A further 5 cm advance sees a major fall of the strong, massive main roof. On failure, two large-scale near-vertical fractures initiate from the longwall faceline and cut through the entire strata (figure 4d), indicating that the strong main roof determines the movement of the above overburden. The gob materials are fully compacted by bending of the overburden. The dislocation of the overburden may cause aggressive periodic roof weightings in the open face area, including the extremely high leg pressures, a massive impact loading or a sudden closure of the shield leg (iron-bound shield). At a shallow depth of cover, a major crack may also develop at the surface and lead to ground fractures and step function subsidence. A mine
water disaster or sand inrush may occur in the open face area through the vertical massive cracks.

After the first major roof fall, the roof overhang length increases with the face advancing and failures in the immediate roof continue (figure 4e). The waste rocks behind the face are not able to fill up the gob area because of a low buckling factor (figure 4f). The overlying strata therefore attain less support from the waste materials in the gob area, which may increase the risk of a massive roof fall. On the other hand, a regular caving of the immediate roof right behind the shield seems to be important and is beneficial for ground stability because it not only fills up the gob void but also maintains a smaller opening width in the face area. Therefore, blasting and hydraulic fracturing methods are commonly used in the field to manually cave in the hard and massive roof strata. As the face advances to 115 cm, the failure zones of the immediate roof extend upward and forward (figure 4g). At 130 cm of face advance, the second massive roof fall occurs with a large-scale sub-vertical crack extending from the faceline to the model surface (figure 4h). Closure of the previous massive crack is found due to the rotation of the roof strata. Water and sand may flow into the open face area once the shield advances to the position of the sub-vertical cutting crack. The interval of the periodic massive roof fall is approximately 65 cm at the current face advance rate.

Model II (2 cm per min). The progressive development of the strata movement for Model II at 2 cm per min of the face advance is given in figure 5. The immediate roof caves in regularly with the face advance (figure 5a). Comparing figure 4 parts b and c, it is found from figure 5b and c that the height of the roof fall is much higher at the current face advance rate. This should not cause significant reverse effects on the ground control because the modern longwall shield can adequately support the dead weight of the immediate roof. A smaller opening width of the face area is maintained in Model II at a faster advance rate, and the waste rock materials present a higher buckling factor and fill up the gob better (figure 5b and c). When the face advances to 70 cm from the start position, two sub-vertical cracks are observed with one above the face inclined to the gob side and the other ahead of the face inclined to the solid coal direction (figure 5d). Since the gob materials are relatively compacted, the loading conditions in the open face area might be better off.

It is interesting to note that the immediate roof falls in the gob area right after the face advances and that the waste rock materials always tend to fill up the gob area and are compacted by the bending roof (figures 5e and 5f). Regular caving of the immediate roof contributes to maintaining a smaller open face area (figure 5g), which as a result improves the ground control. The physical model does not show a second massive roof fall at the final few cuts of the longwall face (figure 5h). The limited length of the face advance in the physical model might be responsible for this, but it can be concluded that a faster face advance rate usually results in a slightly larger interval of periodic weighting. The interval of the periodic massive roof fall is approximately 70 cm at a face advance rate of 2 cm per min, which is slightly larger than the 65 cm for Model I. This agrees with field observations (Wang et al. 2012; Qiao et al. 2014). A mitigated shield loading and better ground control are also expected at the current rate of the face advance because of the waste rocks filling up the gob area.

3.2. Vertical movement of the main roof

Figure 6 gives the movement of the main roof in the vertical direction for each measuring point in relation to the
face advance for both models. For Model I, the main roof is hardly displaced vertically at the beginning of coal extraction. When the first massive roof fall occurs at 65 cm of face advance, a sudden increase is observed. The left-most measuring point P1 presents the largest displacement of 50 mm and stabilizes at this level with further face advance. Pin points P2 to P7 show similar trends, except that the maximum vertical displacement increases slowly with the bending of overburden and impaction of gob materials. The remaining eight measuring points (P8 to P15) at the right side of the model show slightly or unnoticeable movement until another massive roof fall occurs. The second sudden decline in the roof vertical displacement is observed at 130 cm of face advance at the second major roof fall, during which the middle measuring point (say P7) shows the largest drop of 62 mm. This value is unexpected and is taken as error data because the total thickness of the coal excavated in the model is only 50 mm.

For Model II, the main roof rarely shows any vertical displacement until 70 cm of face advance at the first major roof fall, during which there is a sudden increase in the vertical displacement that maximizes at approximately 30 mm for P1. Following the massive roof fall, the measuring points P2 to P8 see a slight increase in the roof vertical displacement before the plateau at the final few advances. Points P9 to P15 barely displace vertically throughout the face advance. No second sudden vertical displacement drop is observed since no second major roof fall occurred. By comparison, Model II has less of a vertical displacement than Model I. This is because the face advances at a faster rate, which allows the immediate roof to cave in regularly after the shield advances, leaving less room for roof displacement.

The vertical movement of the main roof along the model length at each measuring point is given in figure 7. The displacement of the main roof along the model length is almost
flat at the beginning of the face advance for both models. It then shows a sudden increase during the first major roof fall at FA65 (face advance of 65 cm) for Model I and FA70 for Model II. The accumulated displacement then increases mildly with further coal extraction. Another sudden jump in the roof vertical displacement is observed in Model I at the second massive roof fall (see FA130), while the displacement shows no significant increase after 100 cm of face advance for Model II.

3.3. Roof movement velocity

The movement velocity of the main roof is plotted as a function of the face advance at selected measuring points and is shown in figure 8. The velocity maximizes at 65 and 130 cm of face advance for Model I, corresponding to the first and second massive roof falls, respectively. Measuring point P1 at the left boundary presents the largest velocity of 4.6 cm per min at the first major roof fall. A second jump is also observed at 4.6 cm per min for middle point P7 during the second major roof fall, which makes perfect sense because these points are located at the free end of the cantilever roof beam. However, Model II shows a larger roof displacement velocity of 5.9 cm per min at P1 during the major roof fall, indicating that the cantilever beam moves at a larger kinetic energy. The face and longwall shields may experience more dynamic loading at a faster advance rate.

The roof movement velocity along the model length at each measuring point is given in figure 9. It is noted that the velocity is significantly increased at the major roof falls (see FA65 and FA130 for Model I, and FA70 for Model II) and is unnoticeable before and after major roof falls. The second major roof fall at 130 m of face advance for Model I sees an increase in velocity mainly at the right half of the roof, where the maximum value is similar to the first major roof fall (see FA 65 and FA 130 in figure 9a). The rotation of the right part of the roof at the second major roof fall ceased when it came in contact with the left part of the roof, which was originally resting on the waste rocks. This is not observed in Model II.
4. Discussion and conclusion

This paper assessed the influence of the face advance rate on the roof failure characteristics, strata movement, roof vertical displacement and roof movement velocity using physical models. Improvements in the physical models were made to ensure regular caving of the roof strata and highlight the impacts of the face advance rate. In this paper, the authors performed two physical modelling tests in which the two faces advance at 5 and 10 cm intervals at every 5 minutes, respectively. The two parameters in this paper were eventually selected since they represent the minimum and maximum face advance rates, covering the full range in field mining practice. To verify the credibility of the physical modelling results, the authors have provided a relevant analysis to correlate the modelling results with field observations. This should be reasonable to draw the conclusions as presented in this paper and could be optimal for a preliminary study on the face advance rate. Future work may consider the realistic performance of longwall shields in the physical modelling test so that the shield-strata interaction, the roof-floor convergence and face stability can be included. Increasing the number of physical modelling tests will also be considered in future study once a more sound physical modelling test is developed. Important findings of this study are listed below.

(1) The immediate roof caves in regularly with a progressive advance of the longwall face. However, the strong, massive roof determines the movement and failure of the overburden. It forms a cantilever beam overhanging behind the face in the gob area and provides support to the overlying strata. As the weighting interval is reached, the overhanging roof rotates and compacts the gob materials, creating a massive crack on the strata that initiates from the faceline and extends upward to the model surface. This might be responsible for the water and sand inrush hazards in the mining stope, and the ground fractures and step function subsidence on the ground surface.

(2) Two major roof falls are observed with an interval of 65 m for Model I at a smaller advance rate, while for Model II only one massive roof fall is observed with an interval of 70 m, where no further major roof falls are observed because of the limited total face advance length in the physical model. A larger face advance rate leads to a slightly increased roof fall interval. Both models create two major cracks on the strata during the first major roof fall. The cracks in Model I are near vertical and show larger apertures and connectivity, while the cracks in Model II are more inclined and the networks of cracks in different strata layers grow and connect. The immediate roof of Model II caves in right after the advance of the longwall face and better fills up the gob area, which mitigates shield loadings.

(3) The maximum vertical displacements of the massive roof are 50 and 30 mm for Models I and II, respectively. A faster face advance rate more quickly exposes the fresh immediate roof behind the face and allows for regular caving of the immediate roof. Therefore, a larger buckling factor of waste materials is maintained, leaving less room for the massive roof rotation and less roof vertical displacement. The maximum roof displacement velocities for Models I and II are 4.6 and 5.9 cm per min, respectively. The larger overhanging length of the massive roof in Model II (at a faster advance rate) might be responsible for the higher velocity and dynamic hazards. The sudden increase in the roof vertical displacement and velocity indicates the massive roof fall.
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