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Three-zone characterisation of coupled strata and gas behaviour in multi-seam mining

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ABSTRACT

We propose here a three-zone conceptual model in overlying strata of a longwall panel that accounts for the coupled behaviour of strata deformation and gas flow. The model comprises a fractured gas-interflow zone, a de-stressed gas-desorption zone, and a confined gas-adsorption zone. The fractured gas-interflow zone represents the area where mining-induced cross-strata fractures and bedding separations are well developed with high permeability in both the vertical and horizontal directions. Coal seam gas can easily be released from this lower zone to flow down into the mine workings. The de-stressed gas-desorption zone, which lies above the fractured gas-interflow zone, is another significant gas-producing zone in which strata are highly de-stressed. However, mining-induced fractures in this zone are mainly created in the form of bedding separations, which only increase horizontal permeability, and thus the gas cannot easily flow vertically down to the mine workings. In the upper confined gas-adsorption zone, strata depressurisation is limited; the major proportion of coal seam gas in this zone remains adsorbed and cannot be effectively captured. While both lower zones are the targets of gas drainage, the fractured gas-interflow zone is the main source of ventilation gas emission and the prime area of gas control. We have developed an approach to determine the height of these three zones based on the hypothesis of key stratum in strata movement, and verified the approach using gas drainage experience at a Chinese coal mine. The applications of the three-zone concept in selecting appropriate gas drainage methods for varied mining conditions, assessment of methane recovery efficiency, and gas drainage optimisation and maximisation in a mining district of China are also discussed.

1. Introduction

China is the world's largest coal producer, with an annual production of more than 3.5 billion tonnes in recent years. However, a large proportion of China's coal mines produce massive amounts of gas emissions, due to gassy conditions and multiple coal seams within the mines. Because coal seams in China are generally of extremely low permeability and have low gas saturation [1], gas control and management are very difficult. With decades of gas control experience, China's coal mining industry has found that the most effective solution is post gas drainage. Since coal seam methane is a clean energy source, co-extraction of coal and coal mine methane has been widely practiced in China in the last decade [2–5]. This has improved mining safety, productivity and gas utilisation. In 2012, about 10.3 billion cubic metres of methane were extracted by Chinese coal mines, which accounted for about 81.7% of total coalbed methane production. However, gas drainage quality is often poor, with issues such as low and unstable gas flow, low methane purity and low methane drainage efficiency.

The co-extraction system integrates and harmonises coal production, gas drainage and gas utilisation. It is fundamentally designed to take advantage of the significant depressurisation of surrounding coal seams and increase of strata permeability caused by the action of mining, thereby enabling efficient gas drainage from low-permeability coal seams. Efficient implementation of this system relies on clear understanding of the coupled strata and gas behaviour in response to mining.

The overlying strata of a goaf are often categorised into various zones with respect to characteristics of strata break and deformation. Fig. 1 shows a conceptual model of strata zoning that is widely used in China [6]. In the vertical direction, the overlaying strata are divided into the caved zone (I), fractured water-inflow

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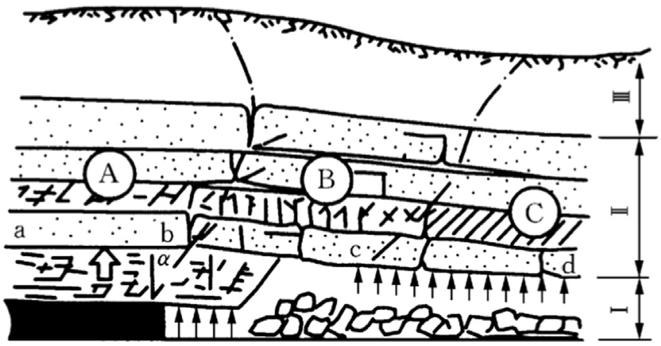

Fig. 1. Conceptual model of mining-induced overburden deformation zones used in China [6].

zone (II) and bending zone (III). In the direction of mining advance, the overlying strata are divided into the coal pillar supporting zone (A), separation zone (B) and re-compacted zone (C). Similar zoning concepts can be found in many other countries [7–12]. Fig. 2 shows another conceptual model, which divides the overburden into the caving zone (A), fracture zone (B), dilated zone (C) and confined zone (D) [12]. The height of the overburden zones is often expressed and estimated as a function of mining thickness [7,10,13]. Table 1 shows the empirical expressions of the height of the fractured water-inflow zone that are widely used in China [13]. This simple method is commonly used in coal mines because it requires no site measurements or computer simulations.

Coal seam gas flows in the goaf can be investigated by approaches such as coupled modelling, computational fluid dynamics simulations, site monitoring with a tube bundle system, and tests with tracer gases [11,14–18]. Although these approaches can provide detailed information about gas flow directions and velocity, they cannot be easily adopted by coal mines. Instead, gas flows are often analysed by characterising mining-induced fractures and their distributions, since they differ in various zones in terms of their density, opening direction and aperture. Fractures that are interconnected with mine workings, as described in [9], form channels for rapid flow of gas and water. On a plan section, the distribution of mining-induced fractures is described as an 'O-shaped' zone, which is likened to a 'gas river' [14]. To achieve a continuous, high flow rate, gas drainage boreholes are therefore suggested to be located in this zone. This kind of analysis is based on assumptions that gas migration along mining-induced fractures dominates the flow, and ignores gas migration through the in-situ porous and fracture networks.

Post gas drainage is often designed and implemented following the three-zone concept of strata deformation (Fig. 1) and fracture distribution characteristics. Since the fractured water-inflow zone represents the area where water can flow down into the workings,

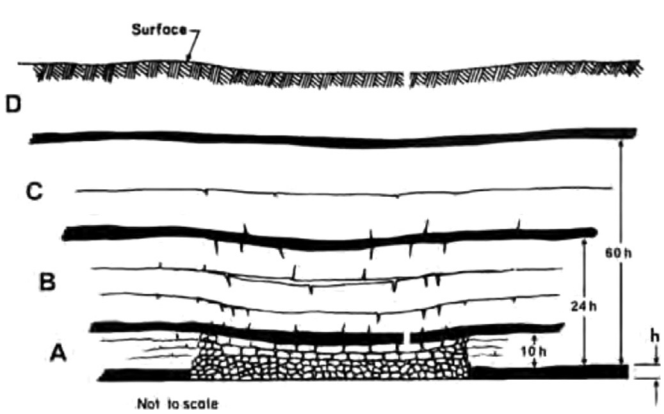

Fig. 2. Overburden response to full extraction of mining [12].

Table 1
Empirical expressions between the height of overlying fractured zone (H_d) and the mining thickness (M) used in China [13].

Strength rank of overlying strata	Height of the fractured zone (m)
Strong	$H_d = \frac{100\sum M}{1.2\sum M + 2.0} \pm 8.9$
Medium strong	$H_d = \frac{100\sum M}{1.6\sum M + 3.6} \pm 5.6$
Weak	$H_d = \frac{100\sum M}{3.1\sum M + 5.0} \pm 4.0$
Very weak	$H_d = \frac{100\sum M}{5\sum M + 8.0} + 3.0$

it is also regarded as the zone of methane emission to the mine workings and the prime target of gas drainage. However, from a resource development point of view, the concept of strata deformation zones is incomplete. It does not fully provide guidance for gas drainage optimisation and maximisation, because it does not directly indicate gas flow characteristics and gas drainability of all zones. As a consequence, gas drainage is often targeted to the fractured water-inflow zone only, and coal seams beyond this zone are neglected – disregarding whether or not they are drainable. An improved approach to characterising both the strata and gas behaviours would avoid these shortcomings and meet the goals of the co-extraction system.

2. A conceptual model of coupled strata and gas behaviours

Efficient co-extraction of coal and methane should effectively control gas to maximise coal production in a safety environment, and also maximise the capture of high-quality gas for further use. To achieve these goals, two aspects need to be essentially and clearly understood and characterised: (a) the extent to which coal seam gas can be effectively depressurised and released and (b) the dominative gas flow direction in the goaf and fractured strata.

The first aspect determines the coal seams from which large amounts of gas can be desorbed and released. Gas desorption in response to mining is a consequence of gas depressurisation, which can be caused by either strata de-stressing or pore water draining. The highly de-stressed zone is often higher than the fractured water-inflow zone. In [19], the height with a vertical stress reduction level of more than 80% was about 160 m at a longwall panel: much higher than the estimated fractured water-interflow zone (60 m) according to empirical experience in the mining area (i.e., 20 times the mining thickness). In unsaturated coal seam conditions such as those in China, a high degree of coal seam de-stressing is required to enable a high level of gas desorption.

The second aspect reflects the extent to which the released gas from coal seams can flow down into the mine workings. This extent is the major target of gas drainage for intercepting gas from flowing into mine workings. It also reveals where methane concentration can be diluted by ventilation air ingress. Although goaf gas flow directions are also affected by many factors, such as reservoir gas pressure, gas drainage and ventilation, permeability dominates. Reference [19] reveals the interactions between mining-induced stress, fracture and permeability changes. These show that (a) the highly horizontal permeable zone is much higher than the highly vertical permeable zone, as shown in Fig. 3; and (b) the change of permeability relates directly to mining-induced stress changes and fractures.

Based on the above analysis, we propose a new conceptual model characterising both strata and gas behaviours, as shown in Fig. 4. We call this model the 'gas three-zone' model to differentiate it from conventional models. The three zones characterised