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Study on Gas Drainage Mechanisms and Techniques in Low-Permeability Coal Seam

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Abstract: This study investigates gas drainage mechanisms and techniques for low-permeability coal seams. It examines coal structure, gas-flow behaviour, permeability controls, and internationally applied drainage methods. Permeability-enhancement approaches, including hydraulic fracturing, hydraulic slotting, and controlled blasting, are evaluated alongside borehole design and operating factors. Sensitivity analysis assesses the effects of coal-seam permeability, gas pressure, and drainage configuration on performance. The study integrates theoretical mechanisms with engineering practices to support safer mining, improved methane recovery, and reduced greenhouse-gas emissions.

Keywords: *Coal permeability; Coalbed methane; Gas Drainage; Hydraulic Fracturing; Low-Permeability Coal Seam.*

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I. INTRODUCTION

➢ *Coal Industry Around the World*

Coal is one of the largest sources of fuel for producing power globally. With low-carbon energy supplies grappling to sustain global power demand, coal is immensely making up for the shortfall, thereby contributing to it being a great source of carbon dioxide emissions associated with energy. Coal production globally is projected to increase in the prospective years, with China and India amongst the nations expected to lead this rise in output and account for two-thirds of global coal consumption in the next years (The Future of Global Coal Production, 2022). The coal industry is present in many countries like China, the United States of America (USA), Australia, Indonesia, Russia, South Africa, India and many others.

The major producers and users of coal in the world are the People's Republic of China (PRC) and the United States, respectively. In these vast coal economies, accidents appear inevitable since coal production is intrinsically dangerous. For the purpose of regulating coal mine safety, both nations have created intricate legal frameworks. These systems have a lot in common (Homer, 2009). The occupational injury incidence among thousand coal mine workers in China has lately risen and hit a new peak recently, while demonstrating a declining trend in the United States. With nearly 75% disease incidence, pneumoconiosis was the most common occupational ailment among Chinese coal mine workers. This disease was reported in 4311 coal miners in 2008, 5997 in 2009, and 12,208 in 2010, accounting for 78.79%, 79.95%, and 87.41% of all work-related ailments, respectively, thereby demonstrating the health effects associated with coal mining and the coal industry (Chen *et al.*, 2012). For Australia, coal production and exports have defined their international trade for years now, directly benefiting the country enormously (Bayari, 2016). This has translated into the livelihood of citizens and mining communities positively, mainly enhancing their living standards and making available worthy benefits (Franks, 2010).

Russia also on the hand has over 200 billion tons of coal deposits, representing 12% of global reserves of balanced coal present in the country, with about 105 billion tons currently being explored. However, the distribution of coal reserves is highly disproportionate with over 80% of them in Siberia, while just 10% of them are in the European region of Russia (Russian Federal State Statistics Service, 2016). In line with the Russian Energy Strategy for the years up to 2030, the output of coal used for power generation is expected to rise as well as the use of the fuel. Thus, 360 million tons of coal was produced in 2015, including 115 million tons of coal stock for thermal power plants (Ministry of Energy of the Russian Federation, 2010; Kuznetsova *et al.*, 2015). As per available data, Russia's coal production was reported to be 433.671Tonne mn in December 2021. This is a rise from the previous figure of 399.664Tonne mn for December 2020 (CEIC, 2021). Generally, these coal production outputs assist the country fire their various thermal plants for power.

Below is a table showing the various coal production from the major coal producers around the world:

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Table 1 Coal Production by Major Countries 2010 - 2021 (Tonne mn)

	Russia	USA	China	Australia	South Africa
2010	322.90	983.70	3428.40	435.00	254.50
2011	337.40	993.90	3764.40	423.20	252.80
2012	358.30	922.10	3945.10	448.20	258.60
2013	355.20	893.40	3974.30	472.80	256.30
2014	357.40	907.20	3873.90	505.30	261.40
2015	372.50	813.70	3746.50	503.70	252.20
2016	386.60	660.80	3410.60	502.10	249.70
2017	411.00	702.70	3523.60	487.20	252.30
2018	441.30	686.00	3697.70	502.20	250.00
2019	440.70	640.80	3846.30	505.60	254.40
2020	399.80	485.70	3901.60	470.00	246.20
2021	434.10	523.80	4125.80	460.30	229.80

(Source: CEIC, 2021)

Coal mining and production generally holds value and is considered a good resource. This resource is one of the main sources of energy in China, and plays a key role in the nation's development economically. Per the official data from the National Bureau of Statistics, Coal constituted 70% of China's overall energy consumption and 77% of its total energy production in recent years (Li, 2012). Coal is China's most dependable energy source and has existed for many years long. The development framework of the coal industry in the country is of immense significance to carbon emission and the protection of the environment (Shihua *et al.*, 2021). The utilization of Chinese coal keeps rising as the nation's economy and industries develop. This valuable resource is especially important for China's rapidly expanding power industry, accounting for almost 80% of total energy generation. (Shealy and Dorian, 2010). Coal accounts for nearly 70% of China's primary energy mix and will remain the most dominant energy source over the next few decades (International Energy Agency, 2008). Gas always stores in coal. Gas-related incidents are one of the most dangerous ones in the coal-mining process. Gas drainage could effectively help eliminate such precarious incidents, as well as provide a clean resource and reduce greenhouse gas effect. Thereby, this research seeks to examine gas drainage mechanisms and techniques in low-permeability coal seams and to determine its benefit towards efficient coal production and utilization.

- *Coal Seam Conditions in Different Regions Around the World*

Coal seams are highly permeable fractured media with a significant interior surface area. During the geological process that results in the generation of coal seams, significant volumes of methane (CH_4) are produced and stored in the coal seam, a process known as coalification (Levine, 1993; Gentzis, 2000). The incidence of gas in coal mining sites is typically influenced by the degree of coalification, the porosity of surrounding rocks, the geological structure, and the deposition thickness and depth of coal seams (Lu *et al.*, 2019; Li *et al.*, 2020a). Geological structure is the primary factor that regulates the geographical distribution of gas content. Varying sealing conditions created by regional and mine structures significantly influence the distribution of gas concentration in coal seams (Moore, 2012; Gao *et al.*, 2020; Quan *et al.*, 2020). As well, higher in-situ stress and increased gas escape distance are also correlated with greater coal seam burial depth, which also favors gas accumulation or sealing. Hence, the coal seam's ability to preserve gas increases with coal seam thickness (Lu *et al.*, 2018b; Kang *et al.*, 2020; Li *et al.*, 2020b). Gas occurrence is greatly a factor of coal structure. The presence of gas is influenced by the physical characteristics of different types of geologically deformed coal, such as porosity and permeability (Guo *et al.*, 2014; Song *et al.*, 2017; Liu *et al.*, 2020), which determines the amount of gas present in the seam.

Every continent has coal seams. The United States (US), Russia, China, Australia, and India have the most coal reserves. Coal is mined in twenty-five (25) states and three (3) primary areas in the United States. In the Western Coal Region of the US, Wyoming is the largest producer with about 40% of the coal mined in the country extracted from the state. The Appalachian Coal Region, which is another coal area within the US, encompasses West Virginia, Virginia, Tennessee, and Kentucky. These areas supply more than one-third of the nation's coal (National Geographic, 2022). The Illinois basin has one of the largest bituminous coal reserves in the United States. This coal deposit is found at a depth of 274 meters (900 feet), it is 2.1 meters (7 feet) thick, and has a high volatile B bituminous quality with an average vitrinite reflectance (Ro) of 0.63percent. Desorbed coal gas content in cores from four wells spaced 15 to 30metres (50 to 100ft) apart ranges from 4.7 to 6.6 cm^3/g (150 to 210 scf/ton, dmmf) and is composed of more than 92% methane gas with minor quantities of Nitrogen gas and Carbon dioxide (Morse *et al.*, 2010).

Amongst the countries of the world, Australia has some of the highest rank coals with the coals of the South Walker Creek region in the northern Bowen Basin, constituting a distinct part, having a vitrinite reflectance (Rv_{max}) of 1.7 to 1.95% (Permana *et al.*, 2013). In addition, the Moura-Dawson Valley area of Australia's eastern Bowen Basin, which contains the Baralaba Coal measures, contains an aggregate of 30m seams of coal with gas concentrations of 9-25m^3/tonne on a dry ash free basis at depths ranging from 300m to 1000m (Day, 2009). Coal reserves in Australia range in age from 15 million to 225 million years and may be found in all states including the Northern Territory (Geoscience Australia, n.d.).

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Coal has been a significant part of South Africa's economy for almost one century and a half. Currently, bituminous coal is the main energy source for domestic power generation as well as the feedstock for the manufacture of a sizeable portion of the nation's synthetic fuels. Additionally, it offers a substantial source of export-based foreign income (Hancox and Götz, 2014). In South Africa, there are 19 coalfields, most of which are in KwaZulu-Natal, Mpumalanga, Limpopo, and the Free State. Gauteng, the Northwest Province, and the Eastern Cape also have small amounts of coal (Department of Energy, 2016). These are Limpopo (Tuli), Waterberg (Ellisras), Soutpansberg West (Mopane), Soutpansberg Central (Tshipise), Soutpansberg East (Venda-Pafuri), Springbok Flats, Witbank, Kangwane, Free State, Vereeniging-Sasolburg, South Rand, Highveld, Ermelo, Klip River, Utrecht, Vryheid, Nongoma, Somkhele and Molteno-Indwe. The coal seam of Limpopo (Tuli) has a depth of 200m and is a synclinal folded basin. Waterberg (Ellisras) is a Fault-bounded graben-type basin, 55m thick, allochthonous, with a depth of 15 - > 400m. The Vryheid coalfield in South Africa has seven (7) coal seams being Targas Seam, Coking Seam (< 1m of depth), Dundas Seam (0.15 – 1.2 m of depth), Gus Seam (extensively developed, 0.5 – 2 m of depth, finely inter-banded, bright and lustrous coal), Fritz Seam (< 0.5m, bright coal), Alfred Seam and Eland Seam. These are a few descriptions of coalfields and seams in South Africa demonstrating the diverse coal characteristics and parameters in the country (Jeffrey, 2005).

China also stands tall as one of the countries with abundant coal resources and will continue to dominate within the world (Shifeng and Finkelman, 2018). China produces one-third of the world's coal, with over half of that output coming from mining thick coal seams (Shihao *et al.*, 2009). Despite being one of the largest coal producers in the world, China's coal seams apparently have quite unfavorable geological characteristics. Most of the regions where coal is now mined have coal seams that are too deep to be surface mined. Therefore, underground mines account for around 96% of China's total coal output. China has made significant attempts to advance coal mining technology since the early 1950s. The long-wall receding mining technique has gained popularity, and roughly 92% of the entire production comes from long-wall faces. The slicing technology is used to extract around 40% of the total production from thick coal seams (Shihua, 2020). China's Xinjiang, Liaoning, Inner Mongolia, and Yunnan all have extremely thick coal seams. Additionally, open-pit mining is typically used in extremely thick coal seams, with the exception of Laohutai coal mine in Fushun, which uses slicing sand backfill mining. East Junggar, Ili, Turpan-Harmi, and Kuqa-Bay coalfields are the four largest integrated coalfields in Xinjiang, which has a 100million ton coal base (Zhang *et al.*, 2015). East Junggar, Turpan-Harmi, and Ili coalfields are notable for having ultra-thick coal seams, which are often above 20meters thick. One seam in the East Junggar Coalfield, for instance, has been estimated to be more than 80meters thick, while the Shaerhu Coalfield boasts a super-thick coal seam that is more than 200meters deep (Dongdong *et al.*, 2019).

In China, the north-south trending Helan-Longmen Mountains structural band divides the Chinese mainland into the eastern coalfield tectonic zone and the western coalfield tectonic region. The Northeast, North, and South coal occurrence structural regions, along with two deformation zones - the eastern compound deformation zone and the middle transitional deformation zone - make up the eastern coalfield tectonic region. This area is distinguished by a variety of coal-bearing strata, a variety of coal-bearing basins, complex coal-bearing basin development, complex coal-bearing basin coal deformation, and striking temporal and geographical variations. Similar in scope to the western compressional deformation zone, the western coalfield tectonic region encompasses the northwest coal occurrence structural area and the Yunnan-Tibet coal occurrence structural area. These regions have clearly better Early-Middle Jurassic coal measurements, with inland lakes serving as the primary coal-accumulating habitat. The Tethys geodynamic system guided the creation and deformation of the coal-bearing basins, and the basins show clear signs of structural inversion over the Cenozoic (Cao, 2020). Additionally, in Anhui, Huainan region's coal mining is primarily characterized by a multi-seam mining scenario that is characteristic of China, where coal is extracted from soft seams with a high gas concentration, high stress, low permeability, and challenging geological conditions. The Huainan area's average mining depth is 875m, and it is rising by 15–25m per year. In Huainan coalmines, the risk of coal and gas explosions grows along with the difficulty of controlling the risk (Liang, 2016).

Also, with regards to coal seam gas or coal bed methane (CBM), China has a known coalbed methane reserve totaling over 37trillion cubic meters, and the third-largest in the world. CBM reservoirs in China, however, are characterized by low permeability, low porosity, and high in situ stress, which leads to low methane concentrations, decreased gas flow, and quick concentration decay. This is due to the deposits' complex geological structures and deep burial depth (Guanhua *et al.*, 2018). Thereby this presents a vivid picture of the coal seam conditions in China, its intricacies and the variations with other coal seams around the world.

- *Significance of Gas Drainage*

Coal seam gas (CSG) also known as coal bed methane refers to the methane released during underground mining, either from the coal seam being mined or from nearby methane-containing rocks. CBM drainage is important in underground coal mining because it helps prevent methane-related accidents, minimizes greenhouse gas (GHG) emissions, and offers a clean source of energy. It ensures the safety of the operations in mining (Karacan *et al.*, 2011). Methane-related incidents, which include, for example, coal and gas outburst and methane explosion, account for a significant portion of all underground mining catastrophes and presents significant risks in general. The property damages and mortality from these methane-induced accidents are always significant (United Nations, 2010). Due to the very complex geological conditions of methane occurrence, which are primarily shown in high methane pressure and concentration, high in situ stress and reduced coal permeability, accident and

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incidence proportion rises; especially as mining depth increases (Hungerford *et al.*, 2013).

As a result, it is essential to monitor closely CBM emissions in the deep coal seams that are vulnerable to methane disasters, and methane must be extracted to an acceptably safe level before coal exploitation to provide a safe and sound mining process and to assure effective mining processes (Black and Aziz, 2008; Lin *et al.*, 2018; Wu *et al.*, 2018).

Methane drainage has two key environmental advantages in addition to increasing mining safety, which are lowering greenhouse gas (GHG) emissions and supplying raw materials and energy that are clean (Hungerford *et al.*, 2013; Salmachi and Karacan, 2017; Zheng *et al.*, 2016, 2017a). The amount of methane released into the ventilation air and the atmosphere is significantly reduced after methane drainage, creating an increasingly positive outcome. Methane drainage is advantageous for reducing greenhouse effect because methane has a GHG effect that is more than twenty times greater than carbon dioxide (over the course of hundred years) and has a negative impact on the ozone layer that is seven times greater than carbon dioxide (Warmuzinski, 2008). This is especially helpful given that humans are constantly grappling with issues around global warming and the atmosphere overtime has been polluted for long with other pollutants (Ye *et al.*, 2017a). In addition, the recovered methane is a significant energy source and may be used to generate great economic advantage. Methane drainage could effectively lower the risk of harmful methane concentrations accumulating in mining operations as well as minimize greatly its emissions into the atmosphere (Lunarzewski, 2019). Thereby, gas drainage is highly significant for the above reasons including maintaining acceptable integrity and safety levels during coal seam mining.

II. RESEARCH CONTENTS AND METHODS

This research provided an in-depth investigation into the mechanisms and techniques for effective gas drainage in low-permeability coal seams, a critical challenge in the coal mining industry. It offered a global perspective on the coal industry, analyzing coal seam conditions across various regions, including an examination of key coal parameters, permeability characteristics, and gas-related properties. The study underscored the significance of gas drainage, emphasizing its multifaceted benefits, such as enhanced resource recovery, improved operational safety, and substantial contributions to reducing greenhouse gas emissions, thereby supporting environmental sustainability.

The research explored the dynamics of gas flow within coal seams, addressing aspects such as coal structure, intrinsic permeability, and the external and internal factors influencing gas migration and flow behavior. It provided an extensive review of gas drainage principles and methodologies, discussing the origins of gas emissions, the parameters affecting these emissions, and the most commonly employed drainage techniques. These included, surface well gas drainage, underground inseam gas drainage, and cross-measure gas drainage. The study also highlighted advanced and innovative gas drainage mechanisms adopted in various parts of the world to optimize gas extraction and enhance efficiency.

A significant focus was placed on permeability enhancement techniques aimed at overcoming the challenges posed by low-permeability coal seams. This included an exploration of gas drainage in stress-relief coal seams and an evaluation of state-of-the-art methods such as hydraulic fracturing, hydraulic slotting, and controlled blasting. The research also addressed the role of stress redistribution and fracturing processes in improving coal seam permeability, facilitating better gas flow and drainage performance.

To ensure practical applicability, the study incorporated a detailed sensitivity analysis of gas drainage performance. This analysis evaluated critical factors, including coal seam permeability, initial gas pressure, borehole spacing, gas desorption characteristics, and drilling angles, providing insights into how these variables influence drainage outcomes. Additionally, the research emphasized the importance of strategic borehole design and placement, along with advanced modeling and simulation techniques, to predict gas drainage efficiency under varying conditions.

By integrating theoretical insights with real-world practices, this study offered a holistic approach to optimizing gas drainage in low-permeability coal seams, making a significant contribution to enhancing resource utilization, operational safety, and environmental performance in the global coal mining sector. Figure 1.1 demonstrates the technical roadmap of this study covering the various chapters.

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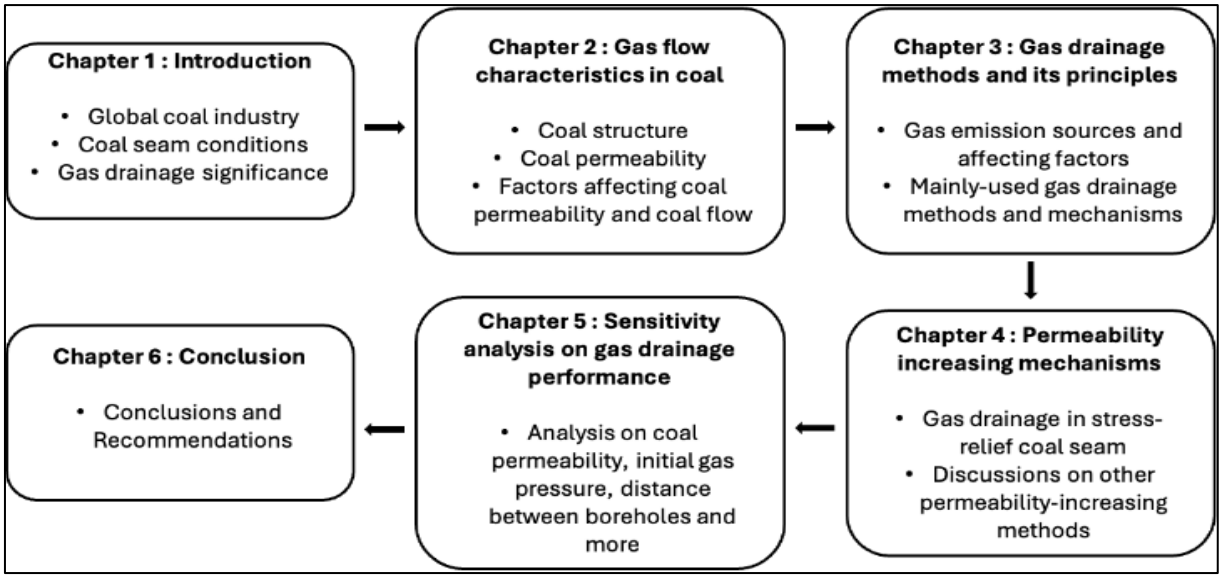


Fig 1 Technical Roadmap of Thesis

Figure 1 summarises the study sequence. It links the review of coal-seam conditions and gas-flow behaviour with the assessment of drainage methods, permeability-enhancement techniques, sensitivity analysis, and the final engineering recommendations.

➢ *Aims and Objectives*

- *Aims of the Study*

The primary aim of this study was to comprehensively explore the mechanisms, techniques, and factors influencing gas drainage in low-permeability coal seams. The research sought to address the challenges associated with low-permeability conditions by identifying effective methods to enhance gas drainage performance, improve operational safety, and optimize resource utilization. A key focus was placed on understanding the interplay between coal seam characteristics, gas flow dynamics, and permeability enhancement mechanisms. Furthermore, the study aimed to provide practical insights into implementing innovative gas drainage strategies, minimizing greenhouse gas emissions, and supporting sustainable mining practices. By integrating theoretical knowledge with practical solutions, the study aimed to contribute to the advancement of gas drainage technologies and practices on a global scale.

- *Objectives of the Study*

The following are the objectives of the study:

✓ To analyze the characteristics of low-permeability coal seams, including coal parameters, gas flow behavior, and factors affecting permeability;
✓ To evaluate globally practiced gas drainage methods and mechanisms, identifying their principles, advantages, and limitations;
✓ To investigate and propose permeability enhancement techniques, such as hydraulic fracturing, hydraulic slotting, and controlled blasting, for improved drainage performance;
✓ To conduct sensitivity analysis on critical factors influencing gas drainage efficiency, including coal seam permeability, gas pressure, and borehole design; and
✓ To develop recommendations for optimizing gas drainage strategies, emphasizing safety, resource recovery, and environmental sustainability.

III. GAS FLOW CHARACTERISTICS IN COAL

➢ *Coal Structure*

Coals are intricate non-homogenous solids with a wide range of physical and chemical characteristics. They also contain compounds that are both organic and inorganic within its composition. Carbon, oxygen, hydrogen, nitrogen, and sulfur make up coal's organic components. The percentages of oxygen and hydrogen normally range between 2- 30% and 2-7%, respectively, while the carbon content, which is 65-95%, increases with coalification. Regardless of coal rank, just 1% to 4% of coal contains nitrogen or sulfur. Many organic substances, mostly hydroxyl and alkyl substituted aromatic and hetero-aromatic rings joined by methylene and ether bonds, make up coal. Even within a unit of coal, the sizes of aromatic rings and the kinds of functional groups vary greatly. Many characterizations have been carried out in an effort to comprehend such a blend or its individual components. Despite these efforts, only a few ambiguous elements with sporadic physical and chemical consistency have been established (Takanohashi, 2016). The two main kinds of constituents that make up coal, a sedimentary rock, are organic carbonaceous macerals and inorganic crystalline minerals. Vitrinite, exinite, and inertinite are the three maceral groups, which together make up the combustible portion of coal. The macerals have various chemical compositions and different origins. The vitrinites are the macerals that are well described. Coals and vitrnites are composed of several macromolecules. These compositions are really intricate. Each macromolecule is made up of structural units, also known as component molecules, which are the macromolecules' subunits that can withstand simple chemical reactions on coal. The challenge of identifying the molecular structure of the organic portion of

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coal is that coal is not structurally dependent on a single molecule but on a complex combination of molecules that vary according to the kind of coal. Coal is a highly complex and heterogeneous rock with developed porosity and both chemical and physical structure. It contains both organic and inorganic impurities. In terms of its chemical makeup, coal is a combination of water and volatile chemicals with minor mineral impurities, as well as high-molecular-weight polycyclic aromatic compounds with a significant ratio mass of carbon, such as toluene, benzene, anthracene, xylene, naphthalene and their derivatives. The supramolecular structure, size, and pore distribution of coal all contribute to its physical structure. The largest pore size of coal, according to the X-ray structural study, is between 80 and 100 Å (angstroms), ranging from 5 to 1000 angstrom (Zhuravlev and Porokhnov 2019).

Among the main elements found in coal are carbon, hydrogen, oxygen, nitrogen, and sulfur. In general, coal may be divided into four basic categories based on its carbon content: lignite, sub-bituminous, bituminous, and anthracite. The precise composition of coal varies depending on its age and origin. Anthracite is the oldest coal kind and has the greatest carbon content, whereas lignite is the latest and has the lowest. In general, coal with a greater carbon content burns more effectively and contains more energy. Minerals including silica, alumina, iron, calcium, sodium, and potassium, which can have an influence on coal's combustion characteristics and environmental impact when burned, are also present in coal in variable concentrations. Coal has a wide range of physical characteristics, such as color, hardness, density, porosity, and many more. For color: coal comes in a variety of hues, including black, brown, and grey. Also with hardness: coal's hardness can vary, ranging from extremely soft and crumbly (like graphite) to extremely hard (like anthracite). With density: coal is very lightweight because it has a lower density than many other rocks and minerals. For porosity: coal may be very porous, with just tiny gaps between the coal particles. Conchoidal fracture indicates coal fractures; thus, when coal fractures, it frequently does so in a curved, smooth pattern. With luster: coal's luster ranges from being dull to being glossy, depending on the variety; and finally for streak: when coal is rubbed on a white, unglazed porcelain plate, it leaves a streak that is either black or dark brown.

Coal's complex and significantly diverse composition makes it structural categorization incredibly challenging. Coal contains a significant amount of coalbed methane, and structural differences greatly affect gas storage and transportation. The major gas storage areas in coal are the micropores that exist inside and between the macromolecules. These micropores will be impacted by the chemical and alignment structures of Coal, which will then indirectly alter how they interact with gas. In fact, a number of earlier investigations have discovered that the chemical makeup of coal directly influences the changes in its micropores. While a few studies have acknowledged that the spatial alignment of polycyclic aromatic hydrocarbons is also a significant component determining the structure of the micropores, the majority of studies have only focused on the effect of chemical and microcrystalline structures on micropores (Charon *et al.*, 2014). It has been discovered that the spatial alignment of the aromatic fringes and the coal's micropore structure are strongly connected. As a result, measuring the variance in coal's spatial alignment and structure will help us better understand how gas molecules interact with coal and how it changes over time.

- *Coal Permeability*

Coal permeability refers to the capacity or precisely the ability of gases or fluids to flow through a coal bed or reservoir. This represents one of the most important properties of a coal-bed reservoir in terms of CBM extraction. The presence of a channel or drainage path in the coal bed is required for gas and fluid circulation through it. If a drainage channel is present, desorbed gas from distant sites flows towards the exit or outlet point and collects there before rising to the surface level via the exit or outlet passage. The coal bed is considered to be permeable in this instance. On the contrary, if there is no drainage channel, which is where the coal bed has considerably no permeability, the desorbed gas is unable to travel and reach the borehole location, resulting in methane gas non-recovery (Datta, 2016). This could render the extraction of coal dangerous and potentially harmful, hence making coal permeability one of the most important factors in CBM drainage and coal production.

The permeability of coal is an essential characteristic in mine methane management and coal bed methane exploitation because it impacts the feasibility of methane extraction. Permeability assessment and estimation in deep coal seams is important in determining the viability of CBM development. The determination of the permeability of coal is based on its fractures, which are regulated by strata temperature, the pressure of gas and strata stress, all of which vary with depth.

Coal is a twin porosity structure with micro-pores and cleats as shown in Figure 2.1. Cleats are a network of organic splits dubbed fractures. Although micro-pores constitute the majority of coal porosity, the cleat structure provides permeability for fluid movement. Cleats are distinguished by two major orthogonal sets of fractures known as the face cleats and the butt cleats. These are usually perpendicular to the framework of the coal bed (Laubach *et al.*, 1998). In coal, intrinsic and extrinsic processes produce cleats with an endogenetic and exogenetic background. Face cleats are generally the dominating, robust through-going cleats that form initially and cut across the bedding surface, whereas butt cleats form later and are often short, discontinuous, and terminate at the junction with face cleats. In certain coals, a third group of cleats develops perpendicular to the coal bed and intersects the face and butt cleats.

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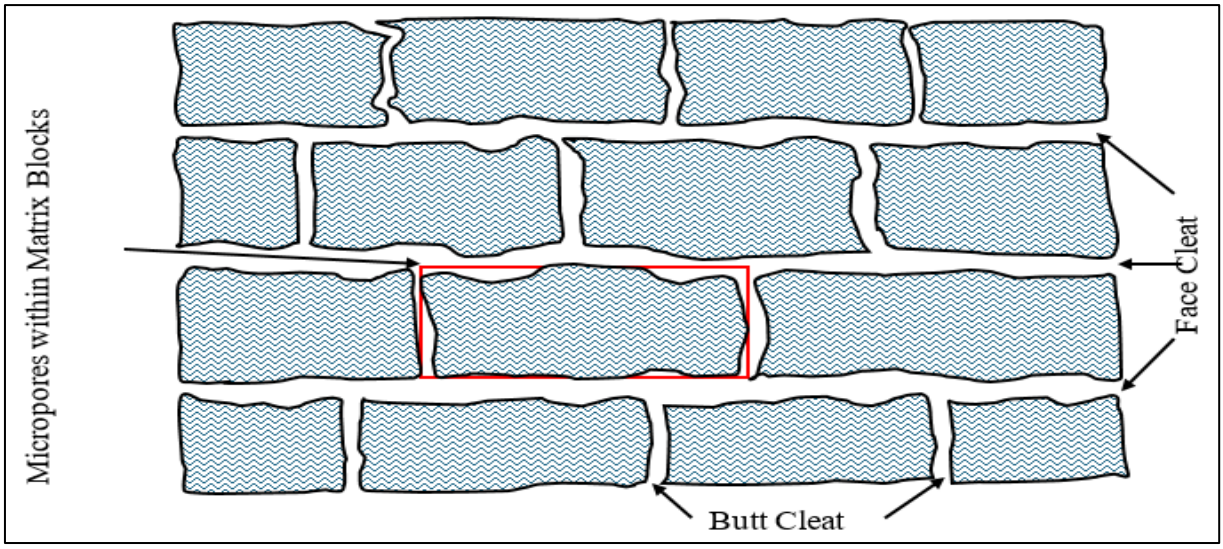


Fig 2 Schematic of Coal Structure with Cleats and Micropores

Figure 2 illustrates the dual-porosity structure of coal. Gas is stored mainly in the microporous coal matrix, while the face-cleat and butt-cleat fracture network provides the principal flow paths toward a drainage borehole.

Many factors influence cleat qualities, including layer thickness, coal rank, material composition, and in-situ stress conditions. The structural network of cleat changes significantly with coal content and is one of the most critical elements influencing coal permeability (Flores, 2014). It has been discovered that the frequency of coal cleats rises from lignite to medium-to-low bituminous coal that are volatile. However, after this stage, with a vitrinite reflectance of 1.3-1.5%, coals have demonstrated a variety of behaviors in terms of cleat frequency, thus declining, remaining stable, progressively reducing, and finally remaining constant. This coal behavior indicates that cleat frequency rises till a vitrinite reflectance of around 1.3-1.5%, although it is less estimable in higher rank coals. As a result, coal rank is crucial in coal permeability because coals with a vitrinite reflectance within the range of 1.3-1.5% are more likely to include an established cleat network, regardless of other parameters.

There have been a number of studies into coal permeability using various methodologies and conditions. The most essential metric in gas recovery which is coal permeability, is determined by the size, spacing, connectedness, and the extent of mineralization of cleats. Laboratory examination of central plugs is widely employed as an indicator of prospective coal seam permeability. However, because coal is very diverse and stress-dependent, laboratory tests tend to be difficult to accomplish and the findings are challenging to comprehend. An improved comprehension of coal permeability and the variables that influence it will be dependent on a more thorough understanding and extensive assessment of the cleat system. Clarkson and Bustin (1997), together with Smyth and Buckley (1993) examined the permeability of several coals and found that vitrite-rich (radiant) coals have greater permeability than inertite-rich (non-radiant) coals. They indicated that the cleat structure influences permeability and that cleat spacing varies with coal rank and coal bed thickness. They were unable, however, to undertake a systematic assessment of the cleat distribution of the investigated coals. Smyth and Buckley (1993) did not investigate the influence of mineral matter on coal permeability, while Clarkson and Bustin (1997) were unable to properly determine the mineral composition of every sample due to the fact that it was measured petro-graphically using visual point count techniques.

Coal seam permeability is an important aspect in determining the effectiveness of coal seam gas extraction for coal seam gas production and coal mine gas drainage. It additionally serves as a significant metric for assessing and controlling the potential risk of outburst, which implies a sudden and forceful discharge of gas and coal or rock elements from underground coal operating areas. A variety of experimental procedures, including the drill stem test (DST), packer test, and slug test, can be used to determine coal seam permeability. In general, these approaches entail monitoring the water pressure or fluid head and flow rate reaction during a regulated injection or withdrawal from an isolated part of a borehole dug from the ground surface. The testing results may be used to assess the hydraulic conductivity and consequently the permeability of a coal seam (Kamenar *et al.*, 2017). These approaches are widely utilized in Australia and a few other nations, including the United States and Poland.

However, in China, the underground borehole flow of gas assessment, which includes monitoring the naturally occurring flow of gas desorbed off coal into an experimental borehole, drilled across the full cross-section of the seam, is used to estimate coal seam permeability in various Chinese coal mines. The approach projects a parameter known as the gas conductivity coefficient (GCC) of coal. This may also be referred to as the coal permeability coefficient in other studies (Xing and Zhou, 2011). The GCC may be defined as the amount of gas that flows through one square meter of coalface of one meter length in a day under specific pressure circumstances, which is discussed below. When converted to permeability, a GCC of $1m^2/ (MPa^2$ day) equals approximately

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$2.5\times10^{-17}m^2$ (0.025mD) of permeability. Zhou (1980) studied and developed the GCC measurement and evaluation method, known in China as the borehole radial flow (BRF) method, which is based on the approximate modular solution of a two-dimensional single-phase planar transient radial flow of gas in the direction of a borehole via a permeable coal seam. The estimate solution was achieved using numerical simulations and the similarity approach (Zhou, 1984). Sun *et al.* (2008) discovered that the approximate solution might face instances in which no solution exists or two solutions exist, in certain cases since there's a discontinuity at the connecting points of the piecewise sections. Notwithstanding its limitations, the BRF technique has been widely utilized in China since 1980 and has become an established means of evaluating coal seam permeability for the coal mining sector (National Coal Mine Safety Administration, 2019). Jiang (1988) found that the BRF approach is more accurate than other borehole gas measurement-based techniques such as the Krichevsky gas pressure methodology, the Marconi gas pressure approach and the Krichevsky gas flow quantity technique.

Using this approach, it has been regularly indicated that the permeability of Chinese coal seams is usually between 0.0001mD and 0.01mD, which is exceedingly low in comparison to the permeability of Australian coal seams, normally in the ranges of 1-100mD (Wang *et al.*, 2017). The 2D solution utilized in the approach may or may not accurately capture reality since idealized models overlook potentially relevant processes, such as gas desorption throughout the observation period. It is logical to examine how well the approach estimates permeability.

Notwithstanding the considerably huge amounts of coal bed methane resources China possesses, the occurrence conditions are usually complicated due to the low permeability of the coal seams predominantly in high gas and outburst coal mines (Fan *et al.*, 2020a; Liu *et al.*, 2021a). Hydraulic fracturing has been explored as a typical technological method for increasing permeability in coal bed methane extraction. This approach does not only enable the optimal exploitation of coal bed methane resources, it also guarantees the safety of coal mine production adequately (Liu *et al.*, 2021b). Presently, low and in some cases ultra-low permeability of tender coal seams leads to challenges such as poor technical success rate, high exploration and development cost, and low single well production, which hinders the extensive development and utilization of coal bed methane (Fan *et al.*, 2020b). Addressing these issues, along with the approach in outburst management and gas pre-drainage would be very useful relative to coal permeability and coal extraction as a whole.

- *Factors Affecting Coal Permeability and Coal Flow*

The permeability of coal reservoirs reflects the flow performance of fluids including coal gas in coal seams, which is significant for the modeling and determination of fluid networks throughout coal seams (Harpalani and Schraufnagel, 1990). Understanding the elements that determine coal permeability is critical for effective coalbed methane exploration. Therefore, multiple studies have been undertaken on elements that influence coal permeability and coal flow such as fissures, geological structures, fracture aperture, coal rank and stratum stress (Shi *et al.*, 2018a, b). Cracks or fractures are the primary pathways for the movement of gas, brine, and other fluids in coal. These fractures in coal are classed as exogenous and endogenous. Endogenous fractures emerge as a result of coal volume shrinkage and internal stresses generated by temperature and pressure during the coal production process, whereas exogenous cracks are created by tectonic features such as faults and folds (Yao *et al.*, 2014). In a recent study, micron-level fractures were analyzed using micro-CT scanning and fractal theory, and the results indicated that micro-crack networks in coals with low ranks had high connectivity, and as the rank of coal grows, its micro-crack structure gets more intricate (Shi *et al.*, 2018b). Coal's permeability evolves in a unique way as an organic-rich dual-porosity medium due to adsorption and desorption. Unlike elastic strain, sorption-induced strain has a nonlinear behavior with continually sorbing gas injections, and both forms of strains are competing processes in producing the volumetric change in coal. The permeability of coal is related to its effective stress and the stress loading and unloading mechanisms. The average permeability damage of a coal specimen is more sensitive to the highest loading stress and the loading-unloading path than to gas-injection pore pressure and holding time. Gas-adsorption-induced swelling greatly minimizes the initial and average permeability damage under cyclic loading.

Geological features significantly affect coal permeability and coal flow. The permeability of coal at a fracture zone in a tensile structure is greater than that in a fracture zone where stress is concentrated (for example, the high-pressure area compressed between tectonic movement and thrust nappe structure). Shi *et al.* (2018a) measured coal permeability under constant confining pressure and effective stress and found that it changes owing to expansion and contraction caused by adsorption, immediately apparent effective stress, and matrix-fracture interactions. The link between coal permeability and pressure sensitivity was investigated using coal samples acquired from the Xinyuan coal mine in Yangquan City. The study demonstrated that, coal's permeability is anisotropic and the permeability along the strike of the understudied coal seam is larger than that in the direction of propensity. These findings demonstrate that coal permeability and coal flow is significantly sensitive to the anisotropy of stress. Shen *et al.* (2010) employed structural curvature to characterize the undulating shape of coal seams and investigated its effect on permeability. They also estimated structural curvature using contours from the bottom of the No. 3 coal seam of the Shanxi Formation in the Qinshui Basin, finding that it has a negative correlation with coal reservoir pressure and is positively correlated with the permeability of coal. These studies investigated the impact of geological variables on permeability and proffered guidelines for further study.

Many other factors influence coal permeability and coal flow. Permeability models for coal are frequently established based on these characteristics or factors. Some models focus on a single component, whereas others examine several different ones. As a result, the permeability models have diverse applications. A number of these influencing factors of coal permeability and coal flow are explained as follows.

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- *Cleat Parameters*

Cleats in coal seams are generally recognized and established as the primary flow channel for gas drainage. That is, coal permeability and coal flow is mostly attributable and influenced by the framework of the cleat structure, with matrix blocks contributing a relatively minor role (Liu *et al.*, 2018). A variety of cleat factors has the tendency to substantially impact coal permeability, including aperture, orientation, tortuosity, connectivity, spacing and mineral filling degree (Xue *et al.*, 2021). These in summary contribute to the nature of the flow of coal and similarly have an impact on the permeability of coal as a key factor.

- *Stress*

Coal seams are typically buried hundreds to thousands of meters deep in the earth, resulting in tight compression due to in-situ pressures or stress. In situ stress is a critical component impacting the permeability of coal reservoirs because it affects the fracture space structure by regulating the density, direction, closure and opening degree of fractures in coal reservoirs (Ju *et al.*, 2019). Coal's permeability is particularly susceptible to in situ stress and often decreases considerably as in situ stress increases. Further, confining stress is often used to quantify coal permeability in laboratory research. In both field and laboratory settings, coal permeability and coal flow are directly linked to applied stress levels. Therefore, the greater the stress and compression of the coal seams in the earth, the more the coal cleats tend to be made narrow and constricted leading to significantly reduced coal flow and permeability (Cui *et al.*, 2007).

- *Gas Sorption*

Coal possesses the unique property of changing volume during gas sorption. Specifically, coal expands when gas adsorbs, and contracts when gas desorbs. Various research studies and laboratory measurements have showed that gas sorption-induced coal volumetric strain can be up to a few percentage points (Durucan *et al.*, 2009). This phenomenon has an obvious effect on coal flow and coal permeability under reservoir circumstances given that in-situ coal cleat porosity is much less than 1% (Ritter *et al.*, 2015).

- *Creep*

Coal flow and permeability is greatly affected by creep due to the softer nature of coal as compared to other rocks. Coal creep usually occurs through four mechanisms, such as cataclastic creep, pressure-solution creep, granular creep and adsorption-diffusion creep (Danesh *et al.*, 2016). During gas drainage, the pressure-solution creep and the adsorption-diffusion creep usually have a greater influence on coal flow and permeability than the other two being cataclastic creep and granular creep. This factor significantly affects coal flow and coal permeability in great measure.

- *Temperature*

Temperature variations have a pronounced influence on coal permeability. At high temperatures, rock thermoplastic strengthening enhances coal compression, affecting permeability and coal flow (Zhu *et al.*, 2011). Additionally, changes in temperature affect gas adsorption efficiency in coal, hence impacting coal flow and permeability immensely (Shang *et al.*, 2019). Even more significantly, temperature variation causes thermal stress in coal, which has the potential to result in deformation of coal and permeability changes.

- *Coal Fines*

Coal fines tend to develop during CBM extraction as a direct consequence of the interaction amongst flowing fluid and coal particulates attached to the cleat surface (Bai *et al.*, 2017). Some of these coal particles may settle inside the cleat networks during their movement process, narrowing or plugging the cleats. That is, the production of coal fines may result in a reduction of coal flow and permeability.

In summary, the flow and permeability of coal reservoirs is mostly determined by the coal structure under in situ circumstances (Fu *et al.*, 2009), alongside all the other factors stated above including cleat parameters, stress, gas sorption, creep, temperature and coal fines. The coal structure is the result of coal deformation under tectonic stress and serves as an evidential representation of the framework for coal flow and coal permeability.

IV. GAS DRAINAGE METHODS AND ITS PRINCIPLES

➢ *Gas Emission Sources and Factors Affecting it*

- *Gas Emission Sources*

Gas emission sources in coal mining vary along a number of aspects. During underground mining, a substantial quantity of adsorbed methane is emitted from the coal, reducing mining productivity and threatening safety of workers and assets. A study by Mucho *et al.* (2000) found that methane is mostly released from three sources which are the active long wall working face and coal mass on conveyer belts, the ribs exposed in the ventilation air and the subsiding strata. Typically, the methane pressure in coal not yet mined is substantially higher than the ventilation air pressure in the operational area. Therefore, methane emissions are facilitated by pressure changes. Despite the fact that this methane emission has decreasing potential with time, it remains a significant source of methane gas in ventilation air and subsiding strata. Methane gas emitting from subsided strata pertains to the collapsed and fractured rock in the goaf region which is the overburden rock. The permeability of this region has the capability to expand beyond hundreds or thousands of times. This causes considerable releases of methane gas from the overburden rock, which subsequently flows through the high-permeability goaf region.

Furthermore, based on research and other study works and experience, two additional emission sources for methane have been observed and identified. These are the surrounding rock layers and the damaged floor rock strata (Zheng *et al.*, 2018a; Zheng *et al.*, 2018b). The floor rock strata undergo stress relief and damage during long wall mining, but to an extent that is lesser than the degree of damage encountered by the overburden strata. Due to this, the methane that was previously trapped in the floor rock strata is then unavoidably released to the operational face of work. In

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addition, methane located in the surrounding layers of rock above the subsided strata which is overburden or underneath the damaged floor strata could seep through the mining-induced permeability enhancement region. Eventually, this methane could make its way to the working face and mining goaf, presenting a serious risk to the safety of mining, lives and properties.

Overall, the general pattern of methane emission from coal seams and surrounding strata is essentially determined by the following, including the mining process, the relative location of gas in the seam and the surrounding strata, and the permeability of the underlying strata. Methane is emitted from coal seams during room-and-pillar mining as the entry and crosscuts expand. As well, methane is also emitted from the roof and floor during the pillar recovery process, when the overlying strata subside and the underlying strata heaves. This process also happens during longwall mining, where the shape of the panels influences methane emissions. Geological discontinuities comprising clay veins, faults, and igneous intrusions, as well as other formation characteristics like sandstone paleochannels, floor feeders and localized folding can all be responsible for sudden, potentially hazardous and unusually elevated emissions into a mine working face. Therefore, emission sources have to be observed keenly and paid attention to, to avert any relevant or related incidents.

- *Factors Affecting Emission*

Methane emissions are affected by a variety of factors, including geological conditions, coal characteristics and mining-process parameters. It is well acknowledged that different coal kinds have variable methane-production and storage capabilities, which is the methane content (Beaton *et al.*, 2006). Vitrinite-rich, bright coals often have a higher methane adsorption capacity than inertinite-rich rank-equivalent coals. The amount of methane released correlates positively with both methane concentration and coal rank. Figure 3.1 depicts the link between mining emissions and methane concentration in Australian coal mines. The fitting analysis findings indicated that when the in-situ methane concentration increased, there was a corresponding increase in the mining emission rate. The rate of emission was almost 4.2 times that of the methane content. Apart from the mined coal, the released methane might also come from surrounding rock strata that contain methane. Kissell *et al.* (1973) observed a comparable relationship while studying methane emissions in coal mines in the United States, finding that methane emissions were around seven times higher than methane content values. The discrepancies in emission rates between the United States and Australia (7 times and 4.2 times respectively) might be attributable to differing mining processes, that is board and pillar mining versus long wall mining, as well as geological properties of the coal resources in both nations.

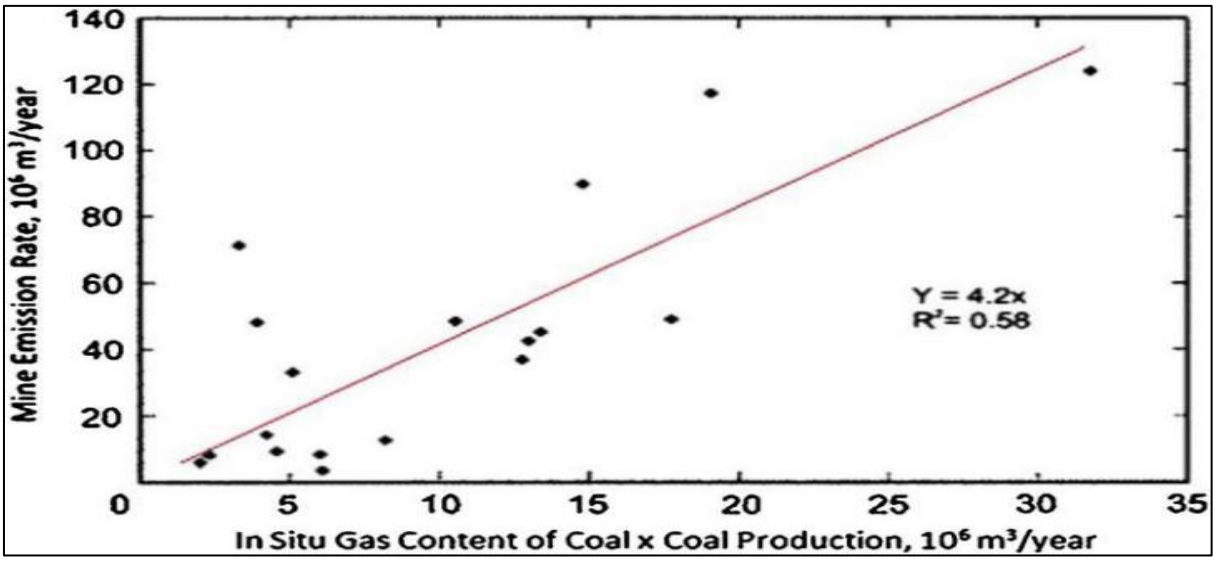


Fig 3 Relationship between Methane Emission and Methane Content (Karacan et al., 2011)

Figure 3 shows the positive relationship between methane content and methane emission. The trend indicates that seams containing more gas generally present a greater emission load and therefore require stronger pre-drainage and ventilation control.

Coal permeability is an essential characteristic that affects methane flow in the coal seam. Thus, it contributes significantly to methane emissions. In general, increased permeability improves gas loss and methane drainage. More methane may escape into nearby seams or be drained away during methane drainage before activities of mining. As a result, methane emissions from mining operations may be low. In contrast, when coal permeability is extremely low, the bulk of methane may be produced during the mining process rather than after degasification. The depth of the coal seam also has an impact on methane emissions. Methane pressure and content could rise as depth increases (Kim, 1977), or they may decrease owing to a variety of reasons, including geological conditions (Salmachi *et al.*, 2018). Nonetheless, greater depth of mining results in a heavier overburden. As a result, long wall mining will cause increased disruption to the overburden strata. The number of caved and cracked zones surrounding the mining panel may increase, similar to the extent of the damage. Thereby, if the methane concentration of a given coal bed remains constant or increases with depth, additional

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methane may be emitted into the mining region from overlying or above strata.

Stratigraphy, tectonics, methane occurrence characteristics, and magmatic intrusions all have a significant impact on reservoir properties and methane emission performance. Multiple studies have found that irregular methane emissions occur due to diverse geological characteristics, such as clay veins, faults, permeability-facies changes, and localized coal seam folding and shearing. Emissions that are abnormal might cause a high concentration of methane in the roadway, among various other hazards. For example, faults have historically been considered as methane flow channels from neighboring strata to the mine operating region. Thus, significant emissions of methane, as well as coal and gas outbursts are more likely to occur at the working face and ought to be addressed when long wall mining comes up against faults.

Karacan *et al.* (2008) evaluated the effect of an impermeable fault on methane emissions and water input during mining. Prior to mining, they carried out vertical borehole degasification in the coal seam. The simulation investigated three fault conditions with borehole lengths of 114m, 343m and 572m, respectively. The results revealed that the amount of methane emission and water input reduced when the mining face went over the fault. The coal between the borehole and the fault had a higher degasification rate than the coal on the opposite side. As a result, the fracture might be seen as a barrier, preventing methane from seeping into the borehole. It should be noted that if the mining direction is the opposite of the current direction, methane emission and flow might rapidly rise when the fault is encountered. As well, if ventilation capacity is insufficient, catastrophic methane occurrences may develop which can be very precarious.

During the mining process, coal becomes fragmented and cracked, releasing an enormous quantity of methane. As a result, in one given coal seam, the amount of methane emitted generally should be proportionate to mining productivity and mining panel sizes, including length, breadth, height, and depth of cutting. Many methane occurrences arise as a result of consistently increased mining activities and production, which can raise the rate of methane emissions and exacerbate the stress on the ventilation system. When the concentration of methane in a working environment surpasses the safety benchmark, methane accidents have a significant tendency to occur. Larger coal-mining panel sizes result in more coal being extracted. As a result, more methane is released from the working face and the gob region. Meanwhile, a bigger mining region may cause more extreme disruptions in the neighboring strata, increasing methane emissions from those locations. Methane emissions from the overlaying fractured zone or the gassy underlying layers of the mining panel are mostly affected by the distance to the coal seam. According to studies, the degree of methane emissions in a given location may be calculated based on its distance from the mining working face. The closer the emission is near the mining panel, the greater the amount of methane released.

➢ *Mainly-Used Gas Drainage Methods and Mechanisms*

Methane emissions from underground coal mines pose significant concerns to mining safety, production, lives and properties. As a result, methane drainage is very important since it is an efficient method of reducing methane content in these underground coal mines and consequently methane emissions into the environment. There are a number of methane drainage methods currently being applied globally. These drainage methods can be classified into three main types based on their borehole trajectory. They are the surface well gas drainage or the surface to inseam (SIS) methane drainage method, the underground inseam (UIS) methane drainage method, and the underground cross-measure borehole methane drainage method. The borehole design and functions of each gas drainage method are discussed and explained below.

- *Surface Well Gas Drainage*

Surface well gas drainage is also known as the surface to inseam (SIS) methane drainage method. This methane drainage method involves drilling a well from the surface of the earth to the specified coal seam or the coal seam target area. This gas drainage method is largely applied and utilized in coal mining regions within Australia according to Palmer (2010). Figure 3.2 depicts a typical SIS horizontal well that is bored from the earth's surface and continues into the coal bed until ultimately intersecting with the vertical production well, where a progressive cavity pump (PCP) is installed according to Field (2004). Furthermore, each coal seam contains two wells drilled in a chevron design to intersect the same production or output well. This provides an advantage for the SIS geometry, demonstrated in figure 3.2. That instance, if point C gets blocked, the obstruction can be simply removed by undertaking injection at point A. This theory further informed MacDonald's (2006) forecasts for the future evolution of the SIS technique, which included changes in lateral diameters and pressure-controlled drilling.

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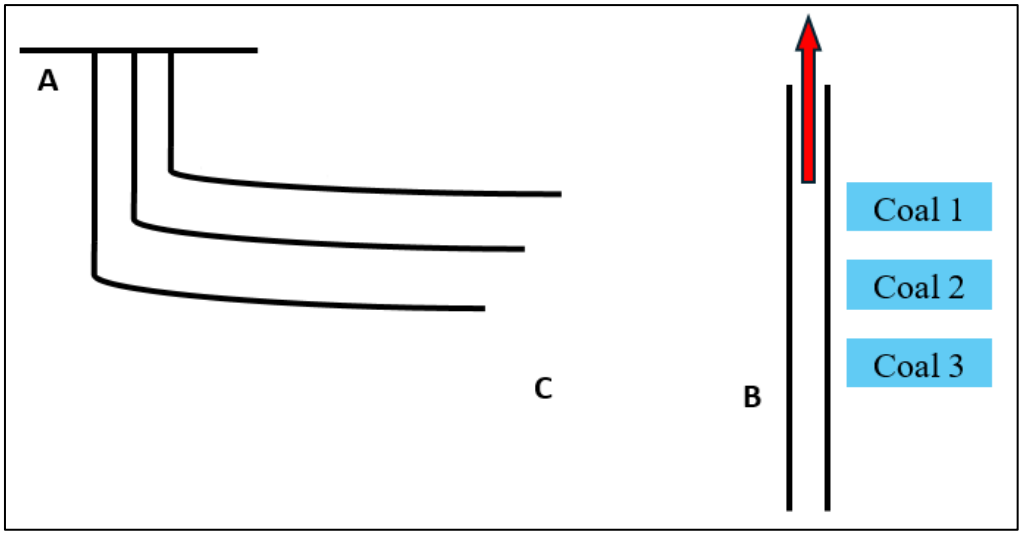


Fig 4 Schematic Diagram of the Surface to Inseam Horizontal Wells (Palmer, 2010).

Figure 4 presents the geometry of a surface-to-inseam horizontal-well system. A vertical surface well is connected to horizontal branches placed within the target seam so that a larger coal volume can communicate with the drainage system.

Also, permeability is an important consideration when selecting coal bed methane completions. Palmer's study suggests using the SIS methane drainage method for coal beds with high permeability varying from 20md to 100md, to ensure effective and desirable performance of drainage.

Additionally, Thomson and Qzn (2009) also found that rotary drilling was commonly used for gas extraction during the 1980s to early 1990s, despite mixed success, as SIS gas drainage involves boreholes from the surface of the mining area to the coal seam region. The varying successes underscore the challenges that occur when drilling deep holes with a rotating shaft. Holes bored at great depths have a high tendency to veer away from the vertical guideline owing to variable rock strengths and other geological characteristics such as dykes amongst others. Conventional longwall methods of gas drainage rely on SIS drilling for both pre and post drainage. Pre-drainage SIS holes are necessary for gas extraction, with an extended lead time before operations begin, whiles post-drainage SIS holes are used for goaf gas drainage. They are distinct from pre-drainage wells due to the fact they are larger and require more spacing. Some countries such as Australia usually employ two types of SIS drilling methods which are, Medium Radius Drilling (MRD) and Tight Radius Drilling (TRD) methods. MRD is a common drilling method for drainage wells in medium-depth seams. This approach provides for a broader spread of boreholes due to the bigger radius of curvature. MRD is preferred in some specific basins, such as the Bowen Basin coalfields, considering its independence from subsurface workings, lower cost, and less requirement for cross-panel UIS drilling. However, MRD systems require a large lead time, varying from 18months to 3 years, to allow for water drawdown. This extended lead time necessitates a larger drill spacing in order to be cost and time efficient. Tight Radius Drilling was developed from the MRD procedure for locations with limited surface area but high gas concentration that must be drained before mining. Instead of drill rods, this type of pre-drainage uses a coil string attached onto a huge drum. TRD provides for closer spacing of pre-drainage holes due to its lower diameter. According to Balusu *et al.* (2006), deviated drilling occurs when a borehole is drilled at an angle to penetrate the coal seam and travel through layers of hard rock, allowing for a bigger region of pressure release and the extraction of more seam gas. This technology was originally employed in an American coal field in order to extract gas from medium-thin seams.

➢ *Underground Inseam Gas Drainage*

- *Borehole Design and Application*

The underground inseam (UIS) gas drainage method is a quite popularly used gas drainage method. With the UIS methane drainage method, an inseam borehole is constructed from the roadway into the coal. Figure 3.3 shows that the UIS drainage method begins with the drilling of a borehole, followed by the installation of a drainage pipe. The exterior end of the drainage pipe is always linked to the roadway's drainage main pipe. The drilling area near the aperture is then sealed using a variety of binding materials, including cement, polyurethane amongst others (Karacan *et al.*, 2011). Ultimately, gaseous methane in coal is drained using negative suction pressure, while the absorbed methane (CH_4) desorbs and provides the methane source of drainage.

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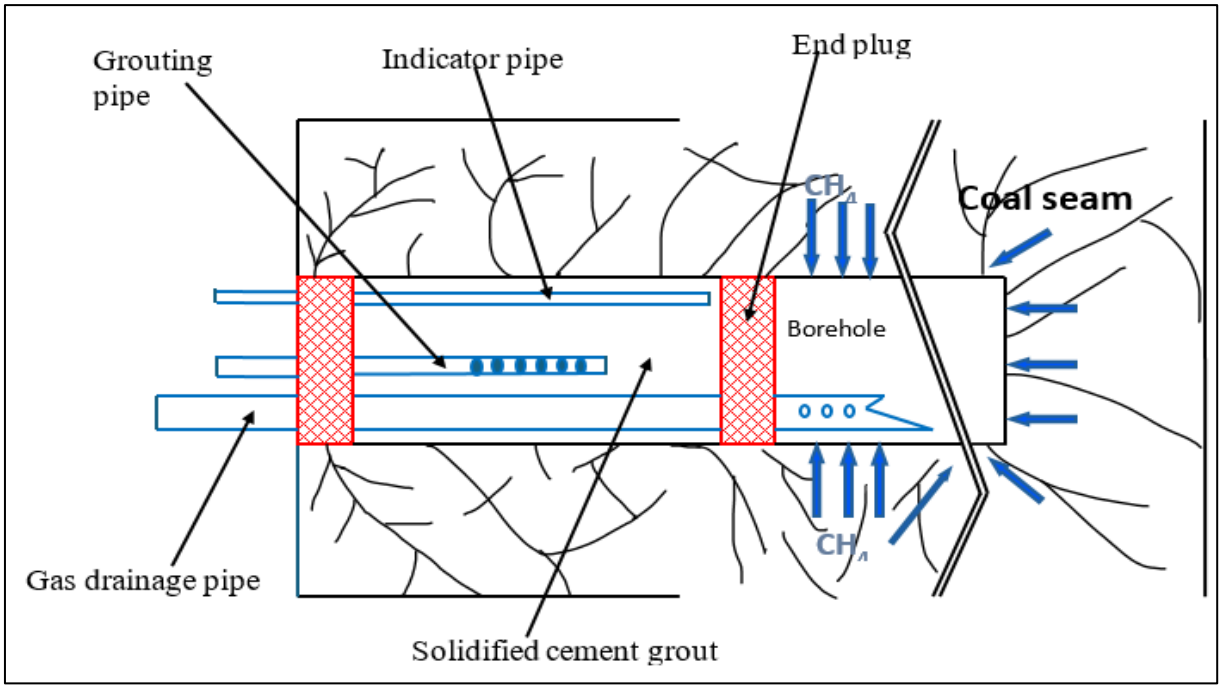


Fig 5 Schematic Diagram of Methane Drainage via UIS Boreholes: Profile of a UIS Drainage Borehole.

Figure 5 shows the profile of underground in-seam drainage boreholes drilled from a mine roadway. The boreholes increase contact with the coal seam and capture methane before it enters active workings.

Prior to 1980, UIS drainage boreholes were usually short, measuring 25-40m in the direction of the working face without suction, with diameters ranging from 43mm to 100mm (Black and Aziz, 2008). In 1980, the West Cliff Colliery carried out Australia's first thorough and routine UIS borehole pre-drainage. Drilling technology has evolved from basic directional rotary rigs to complex machines capable of drilling for over 1600m perfectly (Black and Aziz, 2008). These developments in drilling technology, particularly directional drilling, allow for a variety of drilling patterns, including basic parallel drilling, candelabra drilling (Wynne, 2002), fan drilling (Eade, 2002), and a combination pattern. The parallel drilling pattern is commonly employed in major coal mining countries like China amongst others, because it requires less drilling equipment and procedures than other drilling patterns. Karacan *et al.* (2007) conducted a numerical analysis of the methane drainage advantages of various drilling patterns in the longwall mining panel, and the findings revealed that dual and trilateral boreholes outperformed fewer shorter horizontal boreholes parallel to the working face. Thus, the old drainage schemes are more successful at protecting the safe advancement of the roadway and lowering methane emissions all through longwall mining. As previously indicated, Noack (1998) also examined UIS borehole drainage and reviewed two commonly utilized drilling patterns: fan-shape and parallel drilling. In addition, he introduced Germany's sealing procedure. Based on coal permeability and applied suction pressure, the borehole casing length ought to range between 10m and 20m. The casing material is preferable over plastic tubes because it is more convenient for later coalmining operations. Polyurethane foam is only utilized to seal the annular gap between the borehole wall and casing. Finally, the borehole is attached to the methane drainage pipe beneath the roadway. Many studies have been undertaken to improve methane drainage performance by UIS borehole design optimization. Wen *et al.* (2013) used an orthogonal test to explore the effects of borehole length, diameter, and angle on coal stress alleviation surrounding the borehole, whereas Lan *et al.* (2013) used RFPA software for a similar study. Their findings revealed that the degree of stress alleviation is related to borehole length and diameter, with the drilling angle determined by coal's anisotropic permeability. Irrespective of the drilling pattern utilized, drainage time is an important factor in determining both successful methane drainage performance for minimizing methane emissions and the efficiency of mining activities. Karacan *et al.* (2007) used the GEM and FLAC2D software resources to create a numerical model. This model assessed the impact of UIS horizontal methane drainage borehole designs, borehole spacing, and drainage duration on drainage performance in a Pittsburgh coal bed, as well as methane emissions from the working face. Their results proved very valuable for the gas drainage field. Yi *et al.* (2011) performed a numerical simulation using FLAC software and discovered that stress alleviation surrounding the borehole was better in soft coal than in hard coal. Chen *et al.* (2012a) also conducted a computational analysis of the influence of coal-permeability anisotropy on the methane drainage efficiency of several coal bed methane well designs. They postulated that coal cleats and methane drainage had a shared effect on the permeability anisotropy ratio.

Boreholes can be drilled in a variety of locations for various reasons, according to the UIS borehole application function (Diamond, 1994). These boreholes can be classified into three types of boreholes, namely type A, B and C. Type A is usually drilled in front of a mined-out region, which may assist drain the methane in the active panel, reducing methane

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emissions from the working face and removing the potential of an outburst in this panel. Type B involves retreat drilling in the adjacent developing panel and long-term drainage in the developing panel close to the active panel, which helps to reduce methane emissions into the gob region from the nearby developing panel. Type C relates to the advancing development entries, and it is also used to drain methane in the future panel, potentially shielding the entry development from the methane emissions of the surrounding coal.

In-seam drainage boreholes can also be used to protect roadway excavations in the coal seam. Methane is drained out of the seam prior to roadway construction, eliminating outburst dangers and reducing methane emissions into the excavation working face. This means that the roadway progress rate has the potential to increase significantly (Karacan, 2007; Bohan, 2009). Figure 3.4 demonstrates that by using in-seam shielding borehole drainage in the roadway-development coal region, the monthly advance rate increases from 450m to roughly 800m. The shielding effect of this sort of drainage is more important in longer routes than in shorter ones, as the former typically emit more methane.

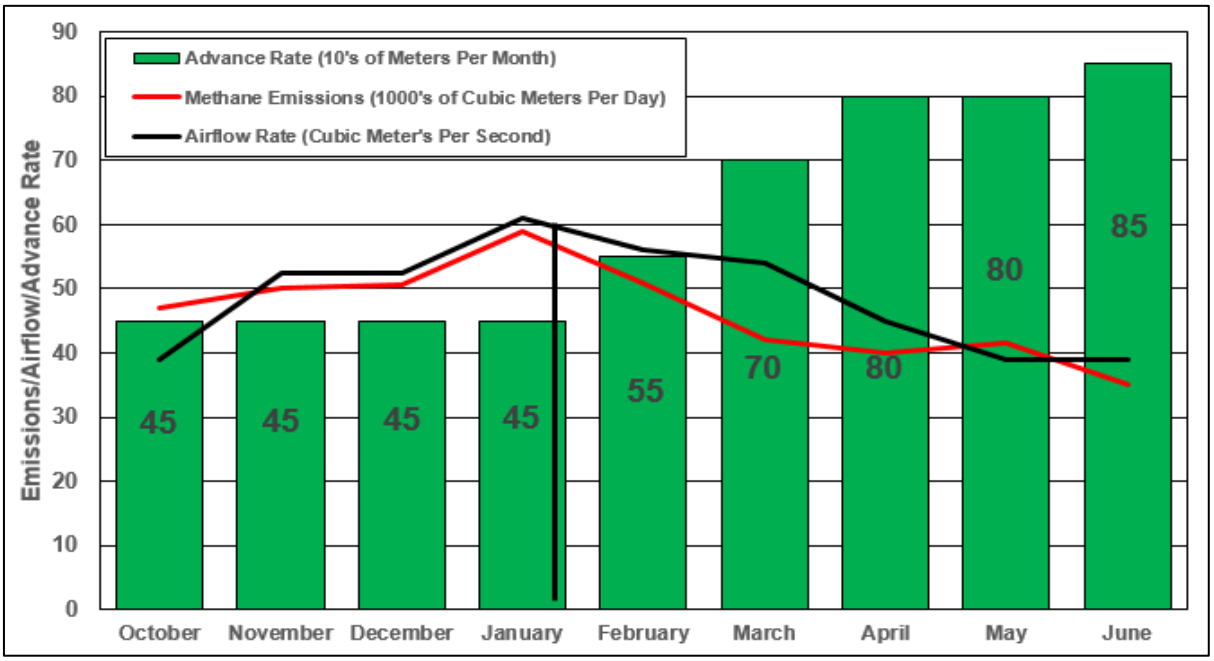


Fig 6 Effects of In-Seam Borehole Drainage on the Methane Emission, Airflow Rate and Roadway Advance Rate (Bohan, 2009).

Figure 6 compares methane extraction, airflow, and roadway-advance indicators during in-seam borehole drainage. The comparison demonstrates how drainage performance should be evaluated together with ventilation and production response rather than from gas flow alone.

➢ *Borehole Sealing*

As previously stated, negative suction pressure is used throughout the UIS methane drainage process to extract methane from the coal seam. This has the potential to improve methane drainage efficiency. However, it also generates a pressure difference between the drainage borehole and the highway, which results in the ventilation air seeping from the roadway rib into the borehole via fractures surrounding borehole (Hu *et al.*, 2012; Zheng *et al.*, 2017b; Zhou *et al.*, 2016). This air loss may reduce the extracted methane concentration as a result of the leaked air in the borehole, affecting methane drainage efficiency. However, the drained low-concentration methane is difficult to utilize and is always released straight into the atmosphere. This might affect the ecosystem and tends to be a waste of clean methane resources (Su and Agnew, 2006). For example, the drained methane content of around 65% present in in-seam drainage boreholes in China decreases to less than 30% during a brief drainage interval (Wang and Liu, 2003). The average percentage of underground drained methane is usually less than 23%, and the methane utilization ratio is just about 33.3% (Xia *et al.*, 2014). These research findings clearly demonstrate the harmful consequences of air leakage on methane drainage performance, hence the importance of avoiding air leakage.

Based on the specific characteristics of the air leakage path, the following methods can be implemented to prevent continuous air leakage:

Firstly, applying air-proof material onto the roadway walls is considered a satisfactory approach to preventing leakages. This can assist prohibit ventilation air from seeping into the broken regions around the borehole. Even though not a lot of studies have been conducted on this strategy so far, it still has some remarkable value for application.

Secondly, blocking coal cracks around the borehole has some great prospects. Lots of studies have been carried out on this strategy. Zhou *et al.* (2009) devised this hole sealing method to seal coal fractures around boreholes and avoid air leaks. This procedure includes two sealing sections. One is short and near the borehole's opening, while the other is lengthy and within the borehole. The two closing portions

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form an airtight compartment. Powder particles are delivered to the airtight chamber by pneumatic conveyance, where they flow into fissures surrounding the borehole, blocking the fractured areas. Furthermore, most existing sealing materials can only seal the borehole space, making it impossible to react to borehole deformation and reach fractured areas surrounding the borehole. Thus, several researchers concentrated on upgrading current sealing materials. For example, Zhai *et al.* (2013) created the flexible gel sealing material. Lin and Zhang (1996), and Yin (2003) also created the fluid-sealing material. All of the materials mentioned above have been shown to better enter fractures. Other enhancements involve incorporating an expansion agent into the sealing material to increase the sealing volume during the sealing-grout solidification process (Hao, 2010) and raising the pumping pressure of the sealing slurry (Zhang *et al.*, 2011, Zhang *et al.*, 2013). All of the aforementioned changes are intended to increase the amount of sealing material flowing into cracks surrounding the borehole and entirely block the air leakage channel.

Third and finally is the sealing borehole effectively method. This approach prevents escaped air from entering into the borehole via the annular gap between the methane-drainage pipe and the borehole. Previous researchers concentrated on improving sealing materials, technologies, and processes to improve sealing quality. Sealant materials usually utilized include cement-based composite sealing materials (Liu *et al.*, 2014; Lu *et al.*, 2019; Zhao and Guo, 1999) and polyurethane foam. Furthermore, Zhang (2013) devised a double-casing-pipe sealing approach to address the drainage borehole collapse problem. On the other hand, sealing length is an important characteristic, since longer lengths entail greater costs, but shorter lengths may result in poor sealing quality. Ge *et al.* (2014), He and Dong (2014), and Sun *et al.* (2012) studied the optimal sealing length using lab experiments and field trials in coal mines.

The third option, which involves effectively sealing boreholes, is the most successful at avoiding air leakage. Because cracks surrounding boreholes are always complicated and extremely small, the first two approaches do not function very satisfactorily.

- *Underground Cross-Measure Gas Drainage*

The underground cross-measure gas drainage method is also a different mechanism to drain methane gas out of a coal seam. A cross-measure borehole is often drilled through numerous layers of rock to reach a coal seam containing methane. Cross-measure boreholes are classified into four separate categories based on drilling site. These boreholes can be drilled from many locations, including the surface type, mined seam roadway type, the roof rock strata type, and the floor rock strata type from the roadway. The first and second types of the cross-measure boreholes are primarily utilized to remove released methane from mining operations, notably in the gob region and overburden strata of the longwall mining panel. Whereas the final two types of the cross-measure boreholes often remove methane from the aimed and specified virgin coal seams (Zheng *et al.*, 2019). Generally, these coal seams have a higher methane concentration with permeability which is considered to be relatively lower, therefore making direct UIS methane drainage not very suitable in this regard due to safety regulations and requirements. Taking into consideration the first and second borehole types; during the course of longwall mining, permeability around the mining panel increases significantly due to the relief of stress and coal degradation. Therefore, methane emissions from the underlying and the overlying layers would enter the mining panel. The degree of methane emission surrounding the longwall panel is strongly correlated with the distance to the mining panel and the local geological parameters (Karacan and Goodman, 2011; Noack, 1998). Furthermore, due to the discharge of methane from the coal seam during the mining operation, there is a significant amount of methane within and surrounding the gob region. In the United States of America, cross-measure boreholes, also known as gob gas vent holes (GGVs), are always drilled vertically from the surface to the expected overlying cracked or collapsed zone of the mining panel to avoid methane emissions from this zone to the working face or gobs (Karacan *et al.*, 2007, 2012). As demonstrated in Figure 3.5, GGVs require drilling from the surface to the fractured roof region; however, they do not interface directly with the system of ventilation of the mine. At the bottom of the borehole, a slotted casing of around 60m in length is installed. The GGVs are usually drilled before the commencement of mining. When mining occurs under a vent hole, the overburden strata sustain fracture and damage propagation. A considerable volume of methane will enter the boreholes via the high-permeability fractured strata. When influenced by mining activities, GGV borehole casing is prone to break in three ways: tension, shear, and compression. Chen *et al.* (2012b) evaluated these three types using FLAC3D software and provided useful suggestions for anti-failure techniques.

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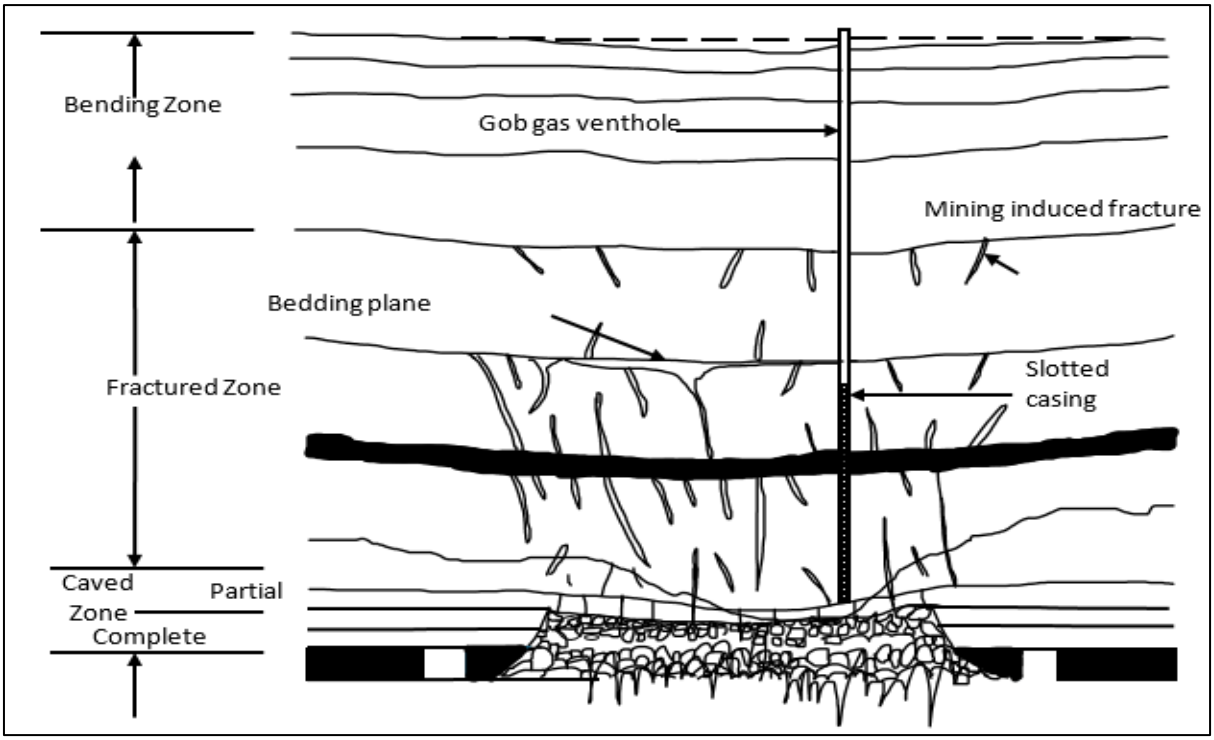


Fig 7 Schematic Diagram of Gob Gas Venthole (Karacan et al., 2007; Singh and Kendorski, 1981)

Figure 7 illustrates a gob-gas venthole extending from the surface into the fractured overburden above a mined panel. Gas released into the caved and fractured zones is intercepted before it migrates toward the working face or return airways.

Cross-measure boreholes drilled from the roadway in the mined seam are also widely utilized. These borehole types are designed to discharge trapped methane from roof and floor rock strata during mining activities. The cross-measure boreholes function similarly to gas vent holes. In Europe, cross-measure boreholes are typically preferred over GGVs due to increased mining depth and relatively lower costs as compared to GGVs (Karacan *et al.*, 2011).

Cross-measure boreholes typically have an angle of 20 – 60 degrees from the roadway. Borehole inclination and spacing are mostly influenced by methane concentration in the roof and floor strata, as well as other geo-mechanical factors affecting borehole stability (Whittles *et al.*, 2007). Campoli *et al.* (1983) used this type of cross-measure borehole to control longwall gob gas (upper Kit tanning coal bed), which involves drilling boreholes with a small diameter from the underground inseam roadway into the fractured overburden strata to prevent methane from entering the coalmine's ventilation system. Furthermore, longwall mining causes the roof rock layers to collapse while relieving the floor strata (Ye *et al.*, 2018, 2017b). Then, a big V-shaped methane release and relaxation zone forms around the mining panel. Three distinct sets of cross-measure boreholes are drilled from the main gate and tail gate to extract roof and floor methane (Lunarzewski, 1998). This system of drainage might prevent the released methane in the damaged overburden and underlying strata from entering the longwall mining working face and the goaf region, hence reducing methane incidents and the combustion of coal in the goaf zone.

The roof rock strata type and the floor rock strata type from the roadway category of cross-measure boreholes are also widely employed in mining operations. Mining coal directly in coal seams with a high risk of outburst is harmful unless the gas concentration is reduced to an acceptable level. Additionally, UIS gas drainage applied directly is unsafe. Cross-measure boreholes drilled from the roof and floor strata of a coal seam are effective safe options for methane drainage. The rock in between the coal seam and the drilling site can ensure the safety of the drilling personnel, asset and operation area.

Figure 8 shows a multilayer set of five coal seams. The coal seam with the lowest outburst hazard is mined first (Zou et al., 2015). According to Wang and Cheng (2012) and Zhou et al. (2015), mining the first-mined coal seam increases the stress relief permeability of the neighboring seams. Two rock roadways are dug in the floor rock layers of the relieved coal seam, followed by cross-measure boreholes from the roadway to the coal seam. Seam contact can significantly improve borehole methane drainage performance. Furthermore, since the drilling area does not lie in the coal seam that has been drained, borehole drilling and methane drainage are largely safe and less hazardous.

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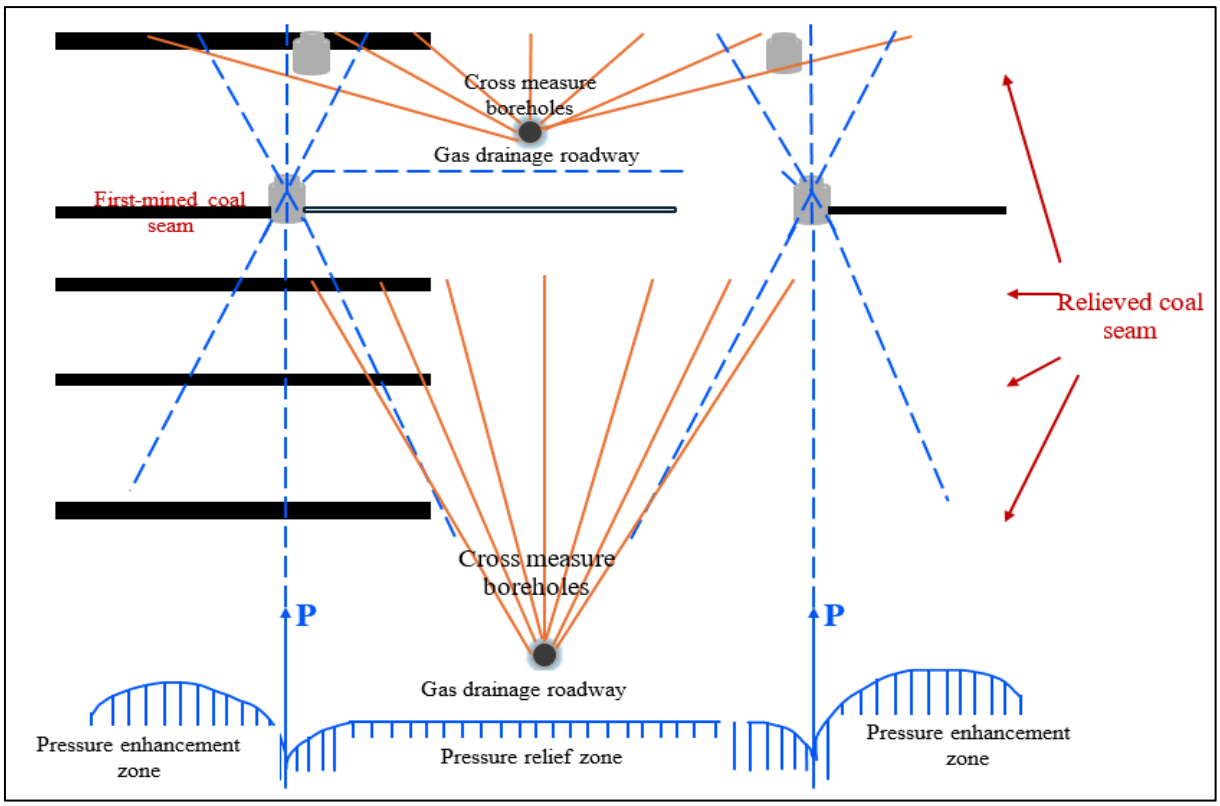


Fig 8 Schematic Diagram of Cross-Measure Borehole Drainage from the Floor Rock Roadway (adopted from Zheng et al. (2018a) and Zou et al. (2015))

Figure 8 shows cross-measure boreholes drilled from floor rock roadways into pressure-relieved coal seams. Mining-induced stress relief increases fracture connectivity, allowing methane from adjacent seams to flow toward the boreholes while drilling remains outside the gas-bearing seam.

Lin *et al.* (2015) investigated the benefits of cross-measure boreholes in the floor rock strata for methane drainage, with the goal of eliminating the outburst hazard in the coal seam above it. That is, coal roadway excavation may be carried out more safely and effectively. Meanwhile, to improve cross-measure drainage performance, hydraulic slotting needs to be carried out in the coal borehole portion to promote coal permeability. Cross-measure boreholes are mostly straight thereby; Hungerford and Ren (2013) studied a directional cross-measure borehole drilling technique. They discovered various drilling procedures and equipment that, to some extent, would broaden the cross-measure borehole's application range and improve its drainage benefits. As a result of the huge borehole length value, sealing performance of cross-measure boreholes is essential, however relatively difficult to achieve.

Liu *et al.* (2014) proposed a novel sealing method for cross-measure boreholes, which included new sealing materials, an automated grouting pump, and a rubber bottom sub. They aimed to prevent air leakage from the rock roadway into the cross-measure borehole. By this means, sealing performance is improved and the efficiency of methane drainage is enhanced.

Drilling cross-measure boreholes from roof and floor strata has become well-known and accepted due to its high safety level and strong methane drainage performance. This gas drainage mechanism is particularly popular and widely applied in China, where coal seam permeability is often significantly lower than other places (Zheng *et al.*, 2018c). The cross-measure gas drainage mechanism, however, has some few downsides. This approach is more expensive than the UIS borehole drainage due to the need for a lengthy rock roadway and several boreholes. The drainage process may also be time-consuming thereby impacting its suitability during considerations on gas drainage types to be used.

- *Good Drainage Examples over the World*

Globally, there are a substantial number of effective and efficient coal seam gas drainage methods and mechanism being applied in various mines. Black and Aziz (2008) investigated methane drainage in the Buli seam, located in the southern Sydney Basin, New South Wales, Australia. Coal and gas outbursts pose a significant hazard to the Buli seam mining activity. As a result, methane drainage is used to reduce methane levels and prevent an outburst catastrophe. Every year, nearly 100,000metres of UIS pre-drainage boreholes are drilled in numerous Buli coalmines. Effective gas drainage yields desirable mining safety, which was observed to be practiced in the Buli coalmines. The study also examined the impact of various parameters such as suction pressure, borehole orientation relative to stress, borehole orientation relative to cleat, borehole length, and borehole apparent dip on total gas production with the following proposed measures to improve drainage performance. These are borehole

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management and maintenance to prevent blockages, enhancing borehole trajectory, ensuring high suction pressures, and maximizing drainage time.

Aul and Ray (1991) also studied the effectiveness of a coalmine's methane drainage system under various drainage periods. They discovered that methane level in drained longwall panels fell by just 30% after approximately two months of drainage and 80% after about ten months. It is indicated that more than six months of borehole draining are required to achieve optimal performance. However, from the standpoint of mining planning and production, the life of an in-seam drainage borehole should not be excessive. Degasification of a mining panel typically requires six to twelve months of methane drainage as a prerequisite before commencing mining (Karacan *et al.*, 2011).

Lin *et al.* (2015) applied cross-measure borehole drainage to the Wangxingzhuang coalmine in Henan Province, China. This gas drainage mechanism is designed to protect the roadway excavation in a coal seam with high gas concentration and reduced permeability. Hydraulic slotting in boreholes is used to promote coal permeability and gas drainage efficiency. Following fifteen days of drainage, the average extracted methane concentration in the borehole is around 26%. Therefore, borehole sealing quality must be increased to optimize drainage performance.

The No. 13 coalmine in Pingdingshan coalfield, China, is prone to coal and gas outbursts. The highest gas pressure and gas content at this mine are 2.5MPa and 15.9m^3/t, respectively. Zou *et al.* (2015) put together a composite cement-based sealing material to mitigate the risk of an outburst. They employed this novel material to plug the cross-measure slotted drainage borehole. The results show that the drained gas concentration might remain between 60 and 80% for approximately one month. This drainage performance is considered better than that of boreholes with typical sealing materials and no hydraulic slotting.

These thereby capture a summary of various gas drainage methods and mechanisms adopted and utilized in different parts of the world.

V. PERMEABILITY INCREASING MECHANISMS IN LOW-PERMEABILITY COAL FOR BETTER DRAINAGE PERFORMANCE

- *Gas Drainage in Stress-Relief Coal Seam*

Extracting gas during mining in coal seam groups characterized by low permeability and high gas content can mitigate outburst risks, resolve challenges associated with insufficient drainage performance and address issues of prolonged gas drainage duration. The safety and dependability of strategies to prevent outburst are crucial for ensuring safe and productive mining operations (Yuan, 2004). Presently, methane extraction is globally employed to minimize the risk of the occurrence of gas accidents or disasters (Yuan and Nong, 2013). The permeability of coal seam is essential as it stands as a crucial factor in assessing the viability of gas drainage (Chen *et al.*, 2013). Due to the intricate occurrence conditions and the low permeability traits of some coal seams, gas extraction is becoming progressively challenging (Han *et al.*, 2016). There are a couple of gas drainage in stress-relief coal seams procedures which are employed to increase permeability. These approaches are discussed in broader detail below.

- *Upward Stress Relief Gas Extraction*

The upward stress relief gas extraction approach for gas drainage in stress-relief coal seam has an extraction principle where the long-distance overlying coal seam is in the bending subsidence zone of the first-mined layer. Following the mining of the first-mined layer, the overlying rock stratum undergoes movement and deformation, resulting in remote upward stress relief. The movement of the rock formation manifests as overall subsidence in the relief layer, with the upper stress relief layer situated in the bending subsidence zone created by the movement of the rock mass. After the first-mined layer is extracted, coal permeability increases, and gas desorption accelerates. Coal subsidence leads to the formation of a minor quantity of vertical non-communicating cracks. A small number of vertical non-communicating cracks in the bending subsidence zone hinder the migration of unloading gas to the mining space of the first-mined layer, thereby relieved gas can only be contained within the coal seam (Yuan, 2009).

Stress relief and expansion of the coal seam cause a significant number of lateral separation cracks in the coal. The horizontal separation cracks facilitate gas flow within the gas layer, with the drainage borehole constructed within the coal seam. Subsequently, stress relief gas flows horizontally from the layer fracture to the borehole due to the suction negative pressure, allowing for the smooth extraction of gas from the stress relief layer. As coal seam gas is gradually extracted, the gas pressure within the coal seam decreases, causing the adsorbed gas to desorb into free gas, which is then extracted via the borehole. The gas content of the coal decreases significantly, thereby promoting gas drainage in stress-relief coal seam for permeability increase (Cheng and Yu, 2003). Figure 9 demonstrates this extraction approach.

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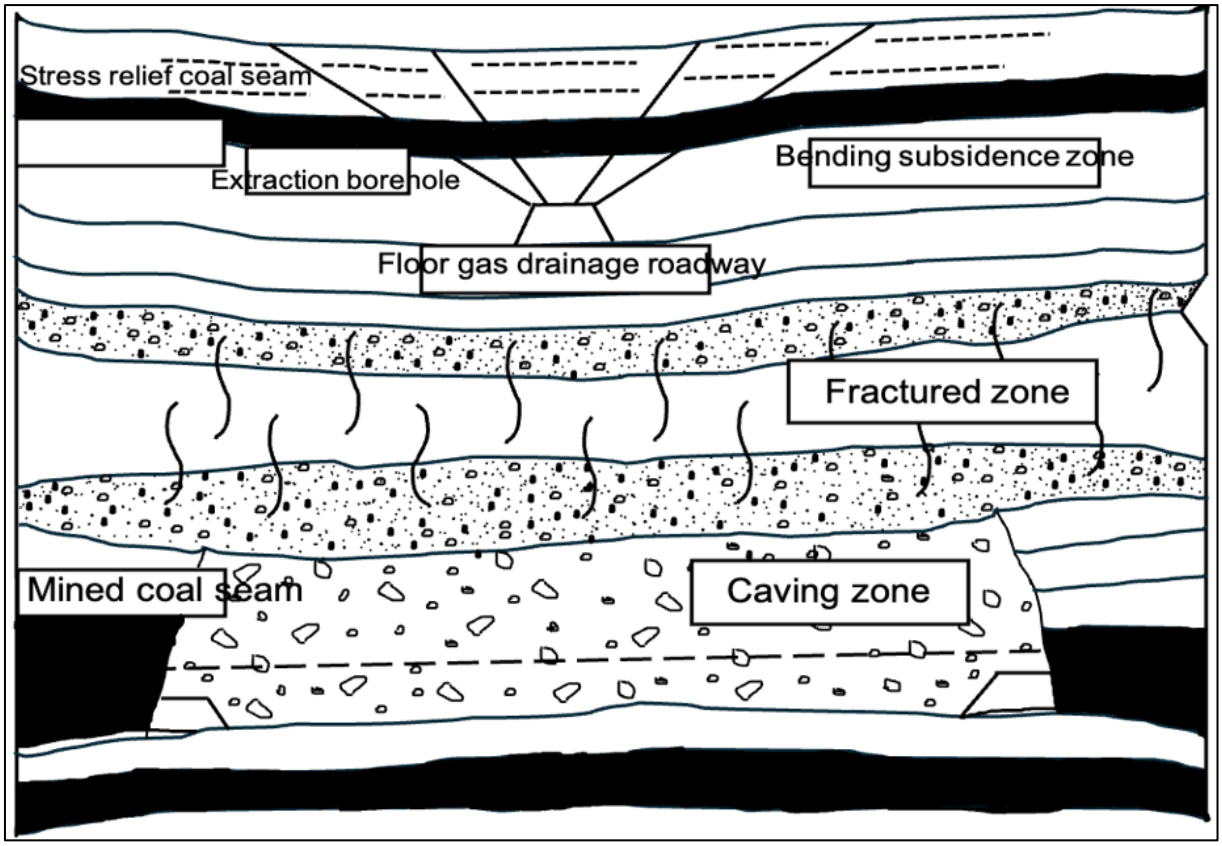


Fig 9 Extraction Method - Upward Stress Relief Gas Extraction

Figure 9 depicts upward stress-relief gas extraction. Boreholes from a lower roadway intersect the overlying protected seam and collect methane after mining-induced deformation opens fractures and increases permeability.

As depicted in Figure 9, prior to mining the first-mined coal seam, the rock roadway is positioned in the distant floor of the unloading layer. The drilling field is set up at a specific distance along the roadway, and boreholes are drilled into the coal seam. During mining activities in the lower mining layer, the upper and lower coal layers begin to undergo stress relief, with an increase in the permeability of coal seam. Gas will be extracted through pre-arranged cross-measure boreholes. Throughout the entire stress relief period, the permeability increases by hundreds of times, reducing gas flow resistance. A substantial volume of stress relief gas is extracted. Furthermore, as the mining face of the mining layer continues to advance, the floor rock roadway and drilling boreholes are not significantly damaged due to the long distance. The gas relieved in the protected area can still be extracted, further decreasing the gas content of the stress-relief zone, thereby guaranteeing the safe and efficient mining of the stress-relief layer.

- *Downward Stress Relief Gas Extraction*

After mining the first-mined layer, the underlying rock mass undergoes expansion and deformation, resulting in floor heave. The expansion and deformation cause the rock mass near the goaf to expand and fracture, leading to vertical and bedding fractures. This increases the permeability of the coal, allowing stress relief gas to enter the goaf through these fractures. This also poses risks to the safe production of the lower stress relief working face. In the lower coal stratum (typically within 40m) far from the lower depressed layer, the connected fissures are not well-developed, and stress relief gas is trapped, which cannot effectively eliminate the outburst danger of the lower depressed layer. However, the interlayer fissures of coal seams are more developed, providing favourable conditions for the bedding flow of relieved gas. Therefore, for the nearby relief layer, it is essential to arrange cross-measure boreholes to intercept the stress relief gas flowing towards the working face of the stress relief layer, ensuring safe coal mining (Yuan *et al.*, 2007). For the lower, distant, depressurized layer, it is necessary to arrange cross-measure drilling to enhance the extraction of relieved gas and reduce the gas content of the coal seam. Further, for the extensive downward stress relief layer encompassing multiple coal seams, the efficacy of stress relief from the first-mined layer is inadequate due to the considerable distance involved. Therefore, it is necessary to mine several upper coal seams to achieve substantial stress relief in the long-distance coal seam. The figure below demonstrates the extraction method for the downward stress relief gas extraction approach.

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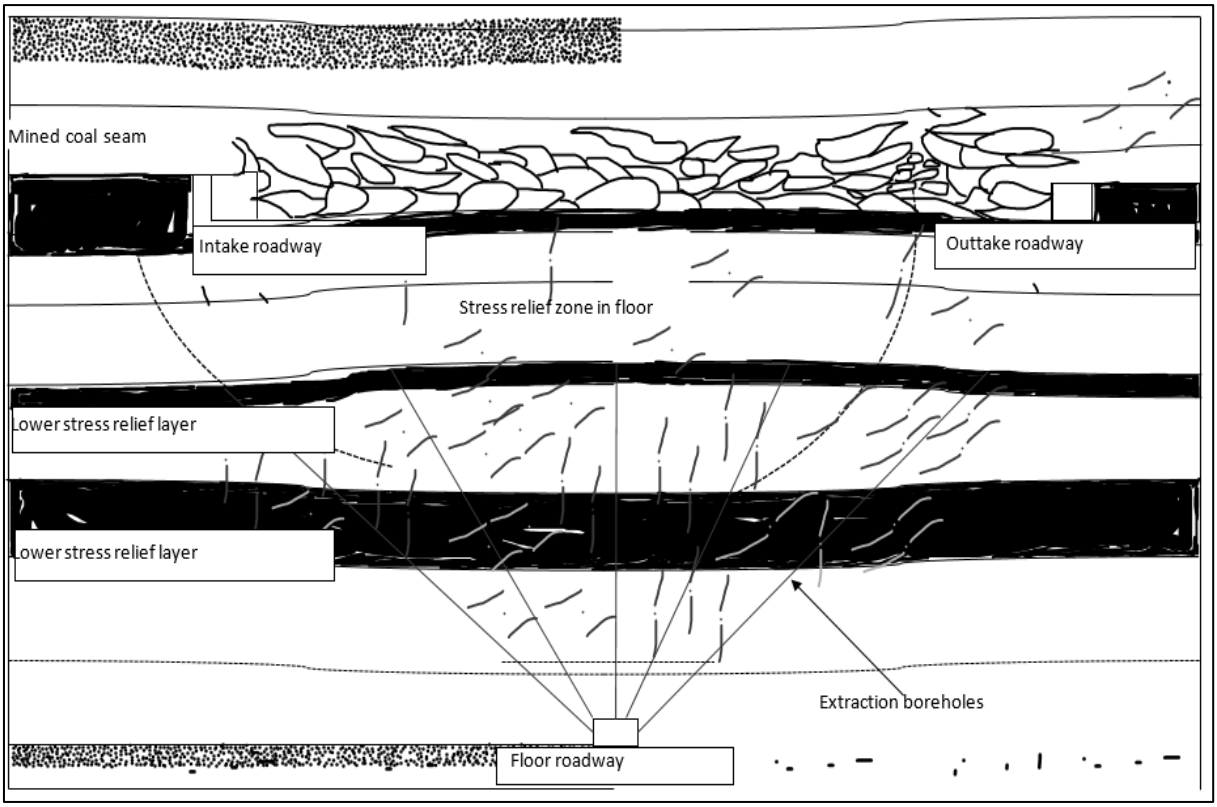


Fig 10 Extraction Method - Downward Stress Relief Gas Extraction

Figure 10 depicts the downward stress relief gas extraction approach for gas drainage in stress-relief coal seam. A floor roadway is established in the floor strata of the lower stress relief layer, with a drilling field set at a specific distance within the roadway. Boreholes are drilled through the lower stress relief layer, as depicted in the figure. The gas drainage project needs to be arranged prior to mining activities. Once the working face reaches the designated position, the relieved gas is smoothly extracted. The floor heave of the coal rock mass is limited compared to the subsidence. Therefore, the floor roadway and cross-measure boreholes in the lower unloading layer will remain intact after the working face advances. The drainage work can then continue, minimizing the gas content of the lower unloading layer as much as possible. This overall contribute to the drainage of gas in stress-relief coal seam.

Figure 10 depicts downward stress-relief gas extraction. Boreholes are directed toward the underlying protected seam so that gas released during unloading can be captured through the induced fracture network.

- *Net-Like Penetrating Boreholes and Surface Well Drilling*

Mining a protective coal seam and conducting methane pre-drainage in a stress-relief coal seam can eliminate the danger of gas outbursts effectively (Cheng *et al.*, 2004; Karacan *et al.*, 2011). The majority of coal seams in China affected by geological tectonic activity are regarded as having evolved into intricate and soft formations (Cheng and Yu, 2007). Consequently, the permeability of the coal seams, ranging from $0.1 \times 10^{-3}\mu m^2$ (with the lowest being $0.7 \times 10^{-4}\mu m^2$ in the Beipiao coal field and the highest at only $1.8 \times 10^{-3}\mu m^2$ in the Fushun coal field), is notably lower compared to those in the Black Warrior and San Juan basins of the USA (Hu *et al.*, 2000). As a result, mining the protective seam stands out as the most effective approach to ensuring the safe and economically viable exploitation of a coal seam prone to outbursts (Dong *et al.*, 2015).

The coal seam positioned above the protective coal seam is referred to as the upper protective coal seam, while the lower protective coal seam is situated beneath the protected layer (Liu *et al.*, 2010). Vertical and delamination cracks within the protected layer will greatly enhance the permeability of the coal strata above (Karacan *et al.*, 2006). In recent years, the primary approach to conducting gas drainage in stress-relief coal seam in China has been through surface well drilling and net-like penetrating boreholes (NPB). This method relies on the specific characteristics of coal seams, gas occurrence, and geological conditions, developed through long-term exploration efforts (Jin *et al.*, 2016; Kong *et al.*, 2014). NPB technology is the most basic and commonly employed method in China for extracting pressure-relief methane or for gas drainage in stress-relief coal seam (Liu *et al.*, 2017). NPB extraction relies on the flexible arrangement of the extraction roadway and the adjustable parameters of boreholes, making it adaptable to various forms of geological conditions (Zhou *et al.*, 2015). The schematic diagram below demonstrates a pictorial representation of the NPB technology used for gas drainage in stress-relief coal seam.

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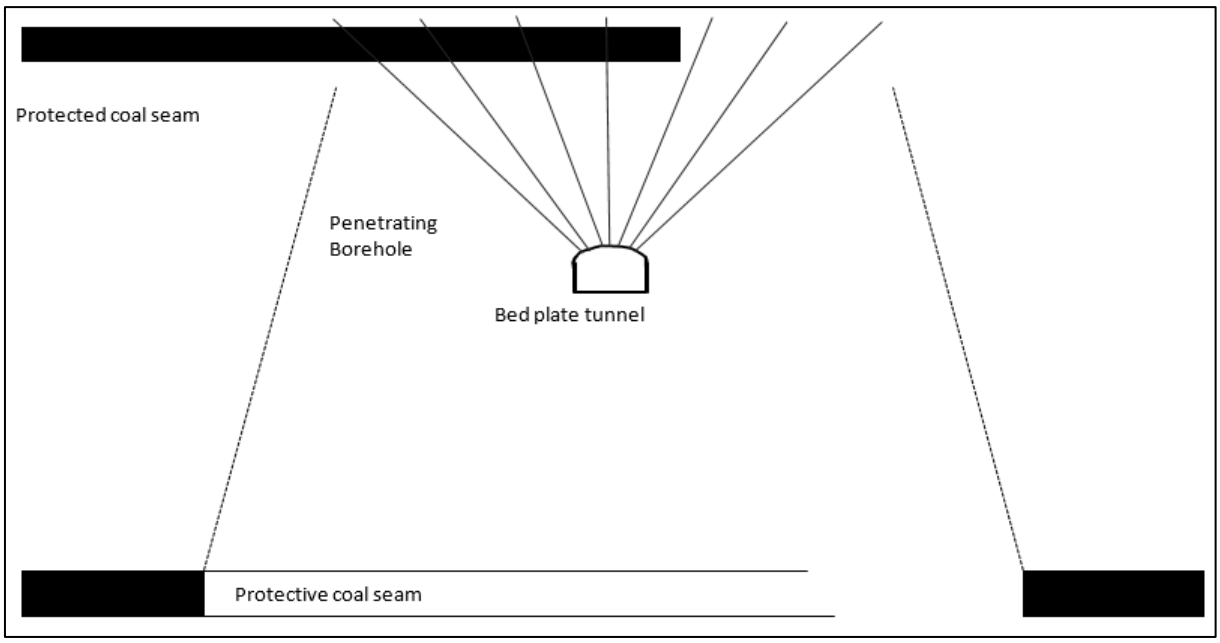


Fig 11 Schematic Diagram of Gas Drainage in Stress-Relief Coal Seam (NPB Technology)

Figure 11 illustrates the NPB stress-relief drainage arrangement. Penetrating boreholes connect the bed-plate roadway with the protected coal seam, providing a controlled pathway for gas released from the pressure-relief zone.

Surface well drillings have also been utilized for extracting pressure-relief methane or conducting gas drainage in stress-relief coal seams for many years now (Sang *et al.*, 2010). Extensive research has demonstrated significant progress in extracting stress-relief methane through surface well drillings from protected coal seams. This drilling method ensures effective methane control not only due to its high flow rate and wide range of methane extraction with high concentrations, but also because it is independent of the engineering constraints of the mining roadway (Li *et al.*, 2014; Liu *et al.*, 2017). The schematic diagram below demonstrates pictorially how this approach is utilized in draining gas present in stress-relief coal seams.

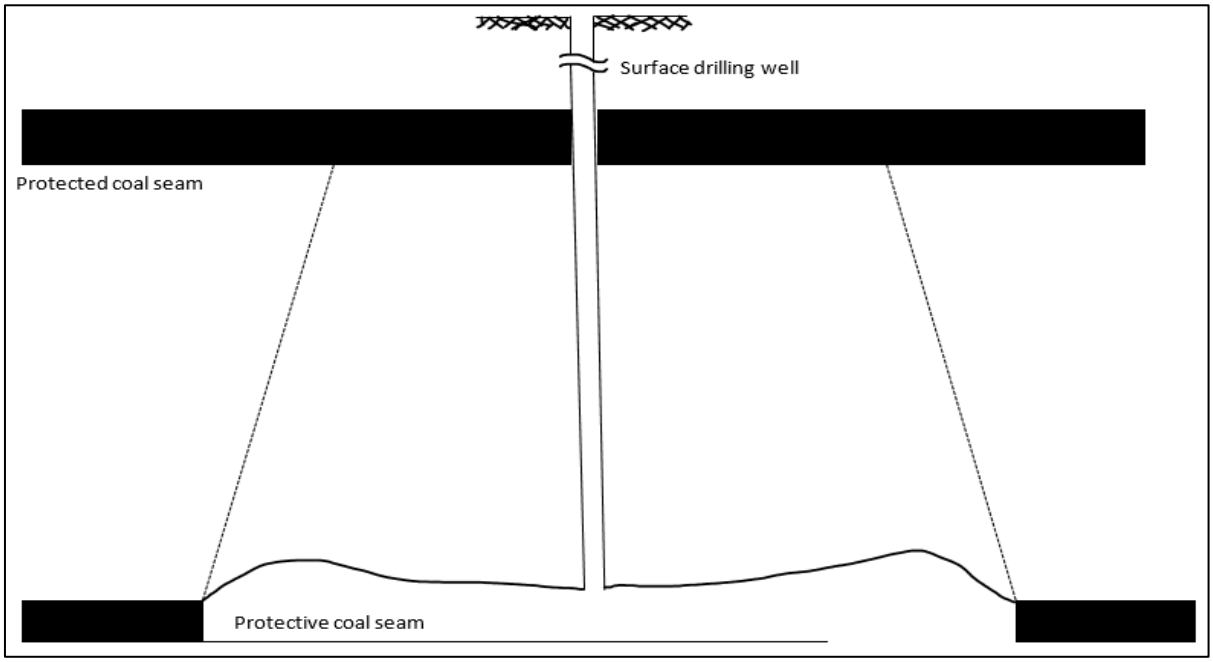


Fig 12 Schematic Diagram of Gas Drainage in Stress-Relief Coal Seam (Surface Well Drilling)

Figure 12 presents a surface-well drainage arrangement for pressure-relieved coal. The vertical well intersects the target zone and withdraws methane after mining has improved fracture connectivity around the protected seam.

In summary, gas drainage in stress-relief coal seam through these various approaches is an essential and effective permeability increasing mechanism in low-permeability coal for better drainage performance.

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➢ *Other Permeability Increasing Methods*

In addition to gas drainage in stress-relief coal seams, which is used to increase permeability in low-permeability coal seams for improved drainage performance, there are other permeability-enhancing methods such as hydraulic fracturing, hydraulic slotting, blasting, etc. These methods utilize external physical forces, not originating from the coal seam, to increase permeability for better gas drainage.

- *Hydraulic Fracturing*

Hydraulic fracturing refers to the process of injecting pressurized water into a sealed borehole to induce tensile fractures in rock (Yang *et al.*, 2004; Zhou *et al.*, 2022). It is an effective technology for overcoming inflow impairments caused by formation damage and for increasing the productivity of coalbed methane (Zhang, 2014). This approach stands as the predominant method for boosting reservoir permeability in the unconventional extraction of natural gas (Dejam *et al.*, 2018; Wu *et al.*, 2018). It involves injecting a mixture of fluid, typically plain water or water-based additives, along with proppant, at sufficient pressure and volume, into the reservoir. When the pressure exceeds the compressive strength of the coal seam, natural cracks in the reservoir expand, extend, with the coal breaking apart in some respect. This process creates an artificial network of fractures with enhanced flow conductivity in coal seams (Dejam, 2019). The study of hydraulic fracturing in coal seams is critical, not only for characterising water inrush related with coupled hydromechanics, but also for resolving gas extraction issues in coal mining. Currently, hydraulic fracturing technology holds a significant role in the exploitation of coalbed methane. Hydraulic fracturing in coal-rock mass has the capability to improve a reservoir characterized by low permeability, low gas saturation levels, and low reservoir pressure, consequently enhancing the production of CBM wells. Furthermore, hydraulic fracturing can also be employed to regulate coal mine gas and mitigate coal-gas outbursts (Li *et al.*, 2015; Yan *et al.*, 2015; Yuan *et al.*, 2015). Hydraulic fracturing connects the initial joints, cleavages, beddings, and microfractures in the coal-rock mass with the propagating hydraulic cracks, forming a fracture network. The fracture network increases coal bed permeability and accelerates CBM desorption and migration (Huang *et al.*, 2012; Xu *et al.*, 2011). However, the fracturing fluid, flowing in the pores and fractures generates water pressure, leading to gas displacement and competitive adsorption (Huang *et al.*, 2016). As well, complete recycling of the fracturing fluid is not possible due to fluid loss caused by the original pores and fractures in the coal-rock mass. Additionally, the fracturing fluid will be absorbed into the pores and fractures under the influence of capillary pressure. Thereby, the pathways for gas migration are obstructed which is known as the water-block effect, and gas desorption is also inhibited (Bahrami *et al.*, 2012). The fracturing process increases the water content of coal and alters the saturation of coal gas and water. Hence, there exists a critical moisture content of coal, below which gas adsorption is inversely proportional to the water content (Zhang *et al.*, 2014). In hydraulic fracturing, as the fracture pressure increases, the pore-size range decreases (Gensterblum *et al.*, 2013). The water-blocking caused by residual fracturing fluid around the fracturing well or borehole persists, and methods to eliminate water blocking are still under development.

During hydraulic fracturing, the stress states surrounding the fracturing well or borehole are initially altered by the transmitted water pressure. Subsequently, hydraulic fractures originate from the surface of the borehole or fracturing well and move outward. The further propagation of hydraulic fractures is then regulated by the water pressure within the fractures. Meanwhile, as the main hydraulic fracture propagates, the pressurized water in the fractures will infiltrate into the coal, creating seepage water pressure. Subsequently, the seepage water flows into the joint and fracture system within the coal seam, leading to the propagation of the original fractures and joints (Lu *et al.*, 2019). Typically, the propagation direction of the original fractures and joints is perpendicular to the orientation of the minimum principal stress. Consequently, there is a certain angle between the expanding branch fracture, known as a wing branch fracture and the original fissure. Following the aforementioned process, a fracture network is established within the coal, comprising original joints and fractures, wing branch fractures, and the main hydraulic fracture.

In hydraulic fracturing, the tensile stress induced by the high hydraulic force surpasses the resistance of the coal seam, causing a macro-fracture to extend completely within the space, forming the main seepage passage. Additionally, the tensile stress causes micro-fractures to extend further. During hydraulic fracturing, the connectivity of fractures and those between fractures and pores is improved. As a result, an interconnected fracture network is spatially formed in the coal seam, which connects gas flow pathways and enhances the permeability of the coal seam. Meanwhile, fractures and fissures are propped open by a proppant such as fine sand with regular roundness and compressive strength, ensuring that newly formed fractures do not close and that the openings of hydraulic fractures are maintained. Thereby, gas can flow through the entire fracture network, hence improving the flow conductivity of the coal seam accordingly (Lee *et al.*, 2016). The table below captures certain physical characteristics of proppants used in hydraulic fracturing.

Table 2 Characteristics of Some Proppants in Hydraulic Fracturing

Type	40/70 Sand	70/140 Sand	Unit
Mean diameter	0.29	0.16	mm
Specific gravity	2.64	2.63	-
Bulk density	1670	1666	kg/m^3

(Source: Lee et al., 2016)

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China uses hydraulic fracturing technology in coal mines with low permeability coal seams to enhance gas extraction efficiency and increase the permeability coefficient of coal seams (Xie *et al.*, 2023; Liu *et al.*, 2022). The initial permeability of such coal seams is often low because it is typically buried deep underground, bearing the weight of the overlying strata, which compresses its fissures, keeping them in a closed or semi-closed state. Hydraulic fracturing employs drilling to pump a large volume of liquid into the coal seam. When the liquid injection rate surpasses the capacity of the coal seam to absorb water, the liquid pressure increases gradually due to the rise in flow resistance. The originally closed fissures within the coal seam will reopen when the pressure exceeds that of the overlying rock layer. Furthermore, when the injected liquid pressure exceeds the tensile strength of the coal wall, stress concentration occurs at the tip of the crack, allowing the crack to extend to the nearest weak surface, resulting in further developed cracks (Ye *et al.*, 2018). The activity and evolution of a crack within a coal seam, induced by hydraulic fracturing, are illustrated in the figure below.

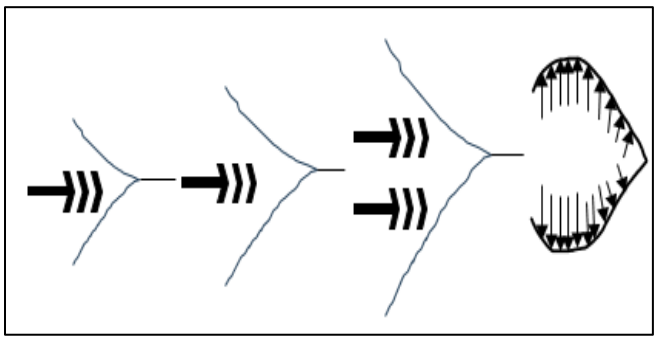


Fig 13 Evolution of Crack Induced by Hydraulic Fracturing in Coal (Wang, 2024)

Figure 13 illustrates progressive crack development during hydraulic fracturing. Fluid pressure first opens existing weaknesses and then extends and links fractures, creating a wider connected pathway for methane flow.

The initially formed coal seam fractures that occurs due to the opening and expansion of the coal seam, enlarge and join to create a fracture network, transforming the gas flow condition of the coal seam from diffusion to nonlinear seepage, to linear seepage and ultimately increasing the coal's permeability (Wei *et al.*, 2020). An increase in cracks may also improve the desorption impact of coal adsorption gas, allowing more adsorbed gas to be turned into free gas, increasing extraction while lowering the gas quantity in the coal seam and improving the efficiency of gas extraction (Ma *et al.*, 2023).

- *Hydraulic Slotting*

Hydraulic slotting refers to the use of high-pressure water jet to cut slots in coal, to facilitate pressure release. This method offers significant advantages for the creation of new cracks and expansion of existing fractures (Lin *et al.*, 2015). Hydraulic slotting technology employs water jets under intense pressure to carve through fractured coal and rock masses; expand borehole surfaces; and swiftly alleviate pressure within coal seams. This approach aims to enhance permeability, reduce internal pressure, and effectively prevent and manage coal and gas outbursts (Li *et al.*, 2022; Wang *et al.*, 2021). As well, this technology is very suitable for coal seams characterized by large thickness, high ductility, high gas content, and low permeability (Ren *et al.*, 2021). Over the past few decades, high-pressure water-jet technology has made significant advancements. It remains environmentally friendly and has several applications across diverse industries (Folkes, 2009). In China, the application of hydraulic mining combined with this water jet technique has already been explored and continuous to be utilized in different sectors including coal mining (Li, 2014).

Some academics have researched hydraulic slotting based on the water-jet approach to enhance the permeability of a coal seam and have found encouraging results (Li *et al.*, 2008). Implementing hydraulic slotting in a coal seam can enhance its porosity and augment the quantity of fractures, thereby boosting the seam's permeability and subsequently enhancing gas extraction efficiency (Lin *et al.*, 2010; Shen *et al.*, 2012). Given the coal and gas outburst disasters that occur during the excavation of coal roadways in high-gas, low-permeability single coal seams, applying the hydraulic slotting technique to increase coal seam permeability is very essential. This technology can significantly enhance gas extraction efficiency, decrease the time needed for gas extraction from a coal roadway, and also minimize coal and gas outburst disasters during coal roadway excavation. Additionally, the technology aids in the effective mining of the working face, as the coal roadway is utilized for transportation and ventilation during mining in the working face (Lin *et al.*, 2015).

The hydraulic slotting system comprises of a power equipment, a control equipment, a slot generator, and connected pipes, as depicted in Figure 14. The power equipment is an emulsion pump, capable of providing a maximum pressure of 30 MPa. The controlling or regulating equipment is the control valve, with the slot generator that produces the slots consisting of drill pipes, a drilling rig, and a water jet bit.

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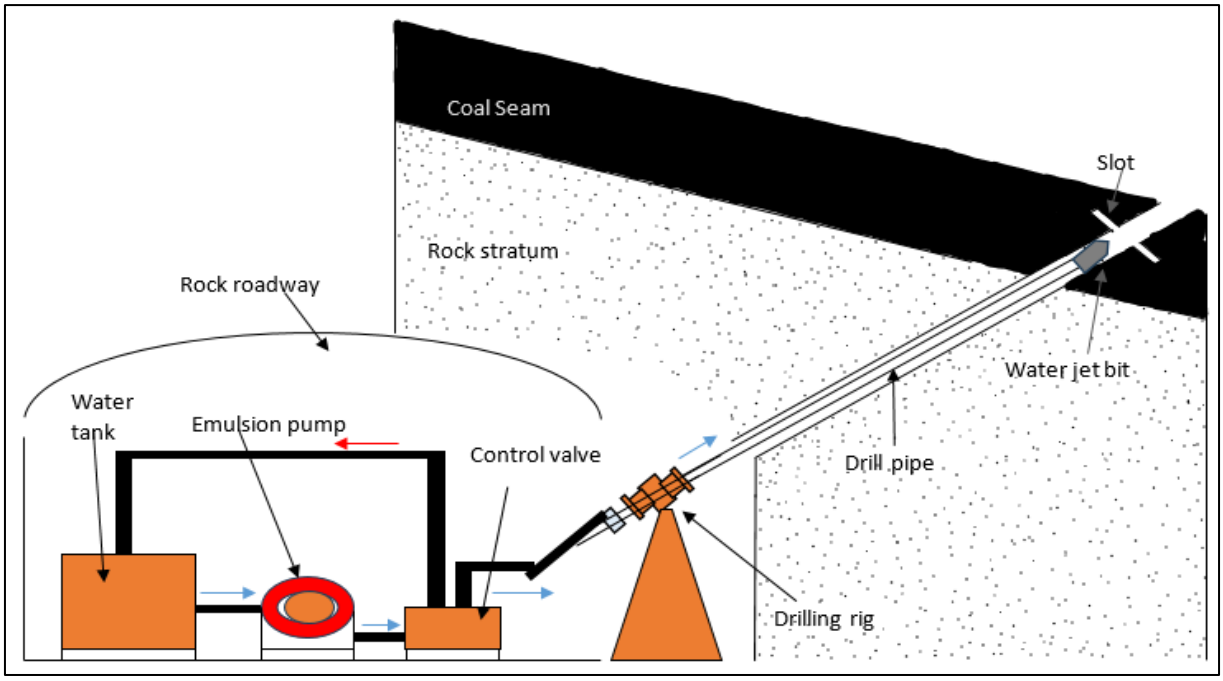


Fig 14 The Hydraulic Slotting System

Figure 14 shows the principal components of the hydraulic-slotting system, including the water supply, pressure-control equipment, drilling pipe, and slotting nozzle. Their coordinated operation produces controlled slots around the borehole and relieves local stress in the coal.

The process of hydraulic slotting primarily consists of three stages which are, slotting preparation, borehole construction, and slotting. Figure 15 illustrates the operational procedure of hydraulic slotting.

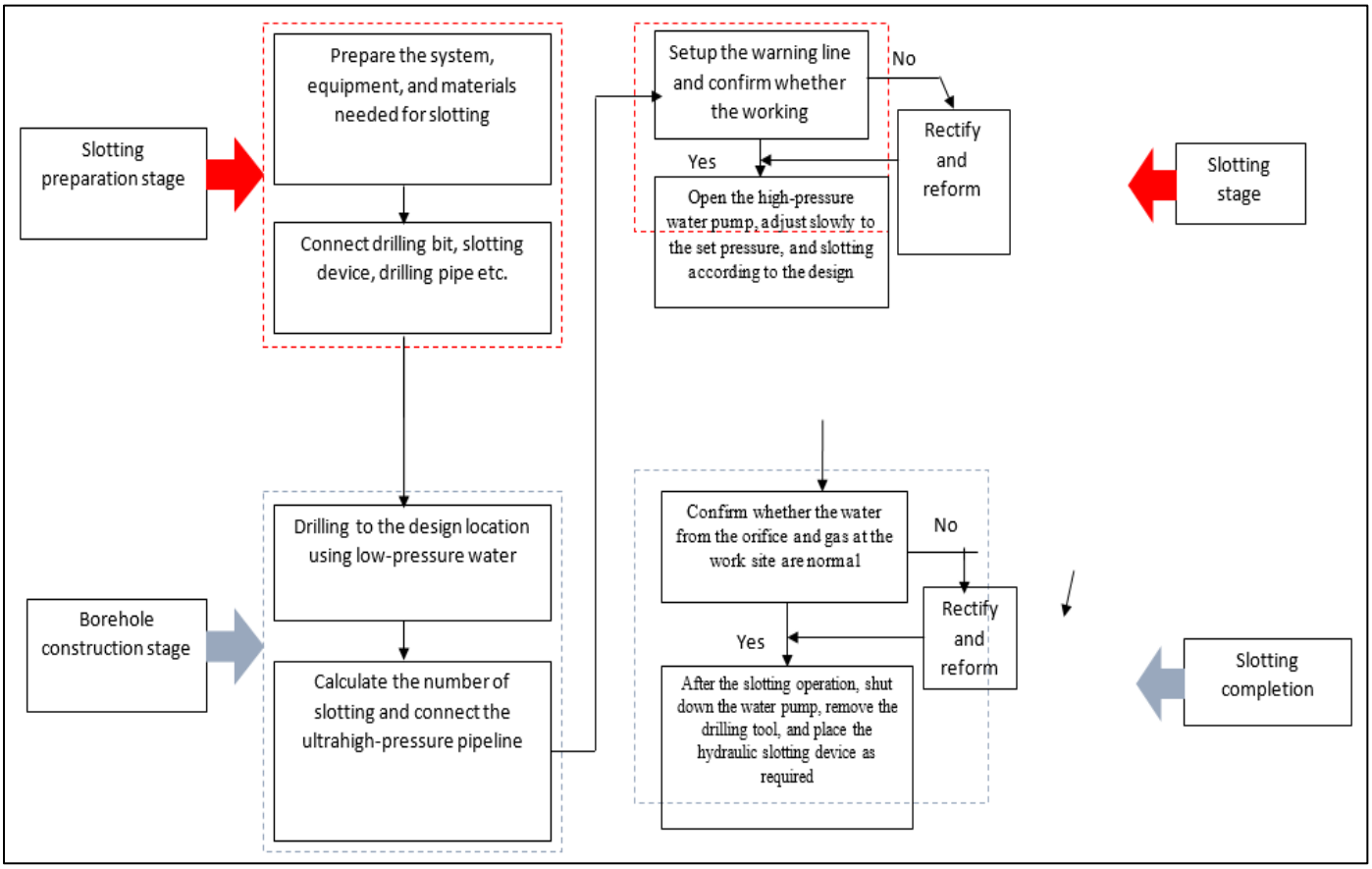


Fig 15 Hydraulic Slotting Operational Procedure

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Figure 15 outlines the hydraulic-slotting operating sequence from equipment preparation and borehole setup through pressure selection, slotting, monitoring, and completion. The sequence highlights the control checks required for safe and repeatable operation.

For the slotting preparation stage, the power supply and the water supply systems must meet the operational requirements for slotting. Additionally, the pumping pipe network and the pumping metering device should be installed and completed beforehand, including the hole sealing material being prepared in advance. Furthermore, the hydraulic slotting system is assembled in stages, including the setting up of the drilling bits, slotting devices, drilling pipes, amongst others. All of this preparation is done to ensure that the slotting equipment functions effectively. The borehole construction stage becomes the next focus. During this stage, low-pressure water is used to drill the borehole to the design depth. It is crucial to install the sealing ring when connecting the drill pipe, and to clean both the thread of the drill pipe and its inner cavity for optimum performance. This then leads to the third stage which is the slotting stage. After drilling work is completed, the low-pressure water tail must be manually removed, with the high-pressure water tail and the high-pressure pipeline connected, including the installation of the warning line. Next, the water pump is activated until water overflows through the borehole, signalling the start of the drilling machine. Finally, the pressure valve is slowly and uniformly adjusted to the specified pressure value. Water then flows through the high-pressure hose into the drill pipe at this point, and the nozzle on the slitter forms a jet to cut through the coal (Cheng *et al.*, 2021). The cutting of the coal takes approximately 20–25 minutes each time. After completing each slotting operation, the pump pressure is released back to zero and then shut down. Following the predetermined slot spacing, the backward slotting method is employed to continue until the slotting operation is complete.

After hydraulic slotting has been performed, a large amount of coal is usually discharged or removed from the slotted borehole. Consequently, the coal undergoes expansion and deformation due to external forces. During this stage, both the volume strain and the permeability of the coal increase significantly. As coal fails and undergoes expansion and deformation, the adsorbed gas transitions from an adsorbed state to a free state, resulting in increased gas release. These changes lead to a significant enhancement in the efficiency of coal seam gas extraction and effectively mitigate the risk of coal and gas outbursts (Lin *et al.*, 2015).

- *Blasting*

Blasting pressure relief technology utilizes the shock wave and stress wave from mechanically induced explosion to dynamically and effectively impact the coal for enhanced permeability increase. The coal is disturbed by the blasting gas, leading to a redistribution of the stress field. The coal seam reaches its yield limit due to the combined effects of the stress wave, shock wave, and gas pressure factors. The width, length, and number of cracks in the coal body increase significantly, as does the connectivity between the pores, thereby boosting the permeability of the coal seam (Kang *et al.*, 2018).

The combination of a shock wave, a huge amount of intense-velocity liquid flow, explosive gases, high temperature, and high pressure in a blasting hole creates a compression-crushing zone that deforms the solid skeleton or structure of the coal mass and destroys the coal seam forming an explosion cavity. Following the shock wave, explosive gases within the blast zone generate a quasi-static stress field that extends into the initial fissures of the cavity wall. Fluid flow then penetrates into the coal mass through radial fractures surrounding the blasting hole. The high-velocity water flow within these fractures carries a significant amount of energy, further extending the initial fractures. This process forms an intersecting fracture network with a radial zigzag pattern surrounding the blasting hole. The stress field at the ends of the radial fracture and the reflected tension wave overlap in the farthest zone of blasting, guided by the control hole. This promotes the expansion of annular fractures and radial fissures, significantly increasing the scope of fracture zones (Sun *et al.*, 2010). Additionally, an intersecting fracture network centred around the blasting hole is formed in the coal seam. This network interrupts or weakens the transmission of tangential and radial stress in the surrounding coal, thereby reducing the stress and facilitating gas desorption. Further, the permeability of the coal around the blasting hole increases, creating favourable conditions to allow free gas drain more easily. Due to the water sealing effect and the properties of water, using a water medium during blasting can prevent the premature loss of explosive gas and extend its action time. This increases the utilization rate of explosive energy and enhances the strength of the blasting stress wave in the water, producing a wider range of fissures. Additionally, water can inhibit the propagation of stress waves or shock waves along the axial direction, favouring radial propagation. When the compression-crushing ring is formed, the shock wave attenuates into a stress wave and propagates through the surrounding medium as elastic waves (Yan and Xu, 2005). While the strength is lower than the ultimate compressive strength of coal and insufficient for crushing, the tensile strength of coal is significantly less than its compressive strength. When the tangential stress associated with the stress wave surpasses the tensile strength of the coal, the coal fractures, forming radial fractures connected to the breakage zone. As the stress wave continues to propagate, its strength gradually diminishes. The stress wave propagates faster than the fractures, causing previously formed fractures to continue extending when the stress wave's peak value attenuates to a level below the coal's strength. However, no new fractures are created. When the stress wave reaches the control hole, it immediately reflects. Although no visible macroscopic fractures form, the quasi-static stress field created by the penetrating effect of the flow causes micro pores in the coal to sustain damage. This process results in a partial recovery of elastic deformation energy stored in the coal, leading to a decrease in stress level and facilitating effective gas drainage (Xia *et al.*, 2016).

The combined action of the tensile stress wave produced by the control holes and the weak-discontinuous waves behind

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the strong-discontinuous wave front creates fractures at the edge of the control hole along the line connecting the blasting hole and the control hole. Ultimately, radial fractures are connected in the direction of the line connecting the control hole and the blasting hole. Fractures occurring in the direction towards the control hole happen earlier than fractures in other directions, limiting the initiation and propagation of fractures in those directions. This results in a perforated fracture surface along the connecting line between the blasting hole and the control hole. In this way, the control hole guides the radial fractures. As a result of the guidance provided by the control hole, the blasting creates a cylindrical compression-crushing ring around the blasting hole in the coal mass. Additionally, a fracture network is formed along the connecting line between the blasting hole and the control hole (Ye *et al.*, 2017). Simultaneously, the release and migration of gas near the blasting hole further diminish the stress within the coal mass. This causes gas emission to evolve into a continuous process, emanating outward from both the control and blasting holes, as illustrated in Figure 16 below.

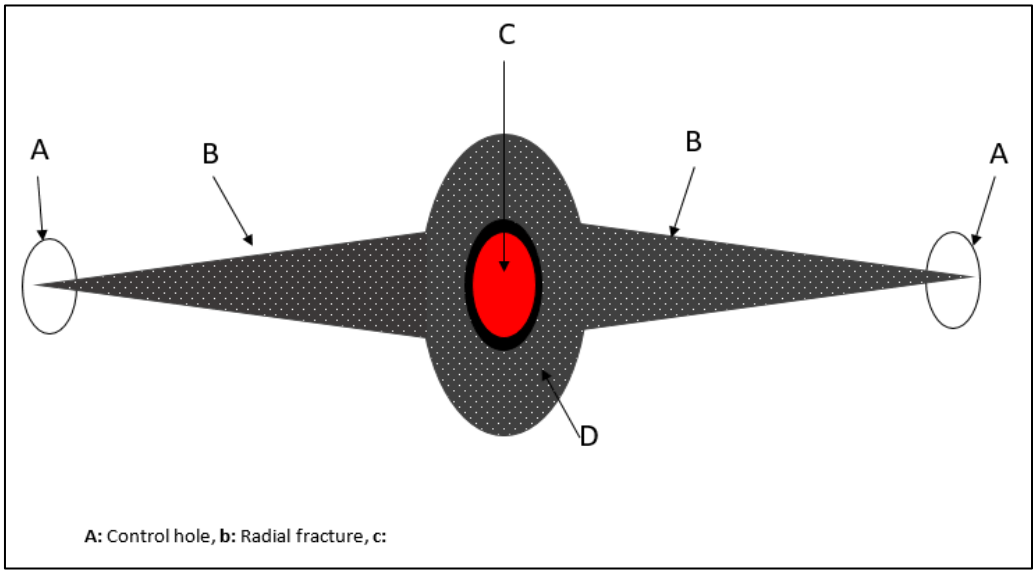


Fig 16 Blasting Technology with Control Hole

Figure 16 shows the controlled-hole blasting arrangement. The control holes define the treatment boundary while the radial fractures and compression-crushing zone around the blast hole increase connectivity without allowing damage to propagate uncontrollably.

VI. ILLUSTRATIVE SENSITIVITY ANALYSIS OF GAS DRAINAGE PERFORMANCE

➢ *Purpose and Scope*

This chapter presents an illustrative sensitivity analysis based on the mechanisms discussed in Chapters 1 to 4. It is intended to demonstrate how a research paper can organise and interpret a trial analysis. It does not report measured mine-site results. The analysis identifies the variables that are expected to exert the strongest influence on drainage performance and explains how they should be tested in a future field or numerical study.

Drainage performance is represented by four observable outcomes: methane flow rate, methane concentration, cumulative gas recovery, and the rate of gas-pressure decline in the target coal. No single outcome is sufficient by itself. A high total flow with low methane concentration may indicate air leakage, while a high initial methane flow followed by rapid decline may indicate a small connected drainage volume.

➢ *Conceptual Baseline*

The conceptual baseline is a low-permeability seam drained by sealed boreholes before mining. The baseline assumes stable pumping, no major leakage, and sufficient monitoring time to observe both the initial response and the decline trend. Each sensitivity case changes one design or reservoir variable while the remaining conditions are held constant. This one-factor-at-a-time approach is suitable for explaining individual effects, although a complete study should also examine interactions between variables.

➢ *Effect of Coal-Seam Permeability*

Permeability is expected to be the dominant reservoir variable. An increase in effective permeability improves fracture flow, expands the volume communicating with the borehole, and normally increases methane flow and pressure decline. The response is unlikely to remain proportional at high permeability because borehole capacity, sealing quality, and pumping limitations can become controlling. Very low permeability is therefore the primary justification for stimulation, whereas moderate permeability may be addressed more economically by optimising borehole spacing and drainage time.

➢ *Effect of Gas Pressure and Gas Content*

Higher initial gas pressure provides a stronger driving force for desorption and flow, and higher gas content increases the recoverable gas inventory. These conditions can produce a larger initial drainage rate, but they also increase the amount

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of gas that must be removed before mining. Performance should therefore be judged by pressure reduction and residual gas condition, not only by the peak flow rate.

➢ *Effect of Borehole Spacing and Diameter*

Reducing borehole spacing increases areal coverage and promotes overlap between drainage zones. The benefit is strongest when the original spacing leaves undrained coal between boreholes. Once adequate overlap is achieved, further spacing reduction gives diminishing returns. Increasing borehole diameter enlarges the immediate flow area, but its influence is generally smaller than the influence of permeability, effective length, and sealing. Larger diameters also increase drilling and completion requirements.

➢ *Effect of Sealing Quality*

Sealing quality is a high-sensitivity operational factor because leakage affects both performance and interpretation. A deteriorating seal can increase measured total flow while lowering methane concentration. This false improvement can lead to incorrect conclusions about the reservoir response. Seal integrity should therefore be checked before attributing a performance change to permeability enhancement or pumping pressure.

➢ *Effect of Extraction Pressure and Drainage Time*

Increasing extraction pressure generally increases the pressure gradient toward the borehole, but the benefit is limited by leakage and flow resistance. The sensitivity curve is expected to rise initially and then flatten. Drainage time has a cumulative effect: longer operation permits gas from less-connected matrix regions to reach the fracture system. However, the incremental recovery per day declines with time, so the practical drainage period should be selected from both safety targets and the declining recovery rate.

➢ *Interactions between Variables*

The variables do not act independently. Hydraulic fracturing has little value if the new fractures are not connected to a well-sealed borehole. Close spacing cannot compensate fully for collapsed or water-blocked holes. High extraction pressure may improve flow in an intact system but worsen air leakage in a damaged system. The most useful optimisation therefore combines reservoir improvement, sound borehole completion, and controlled extraction.

➢ *Illustrative Comparison of Trial Cases*

The qualitative comparison below shows how trial cases can be reported before numerical or field data are available. The rankings describe expected relative behaviour and should be replaced with measured values in a formal study.

Table 3 Illustrative Comparison of Gas Drainage Trial Cases

Trial case	Main change	Expected methane flow	Expected concentration	Primary concern
Baseline	No stimulation	Low	Moderate to high	Slow pressure decline
Case A	Higher effective permeability	High	High if sealed	Fracture persistence
Case B	Closer borehole spacing	Moderate to high	High	Drilling cost
Case C	Higher extraction pressure	Moderate	May decrease	Air leakage
Case D	Improved sealing	Stable useful flow	High	Seal durability
Case E	Longer drainage time	Declining daily flow	Stable	Schedule impact

➢ *Engineering Interpretation*

The illustrative ranking indicates that permeability enhancement and sealing quality should receive the highest priority in a low-permeability seam. Borehole spacing and drainage time remain important design controls, while extraction pressure should be optimised rather than maximised. A field trial should use at least one untreated control zone and should monitor the same variables over comparable periods.

A defensible performance assessment should report baseline conditions, treatment parameters, borehole geometry, seal construction, suction pressure, methane concentration, gas flow, cumulative recovery, and pressure decline. Reporting only the best-performing borehole would not demonstrate that the method is repeatable. Variation between boreholes should be included and possible causes should be discussed.

➢ *Limitations and Next Steps*

This trial chapter is qualitative because the supplied material does not contain a complete experimental data set for sensitivity modelling. Its purpose is to establish a transparent analytical structure without fabricating results. The next stage should populate the framework with field measurements or a calibrated numerical model, define the tested parameter ranges, calculate normalised sensitivity coefficients, and compare predicted and observed drainage performance.

VII. CONCLUSIONS AND RECOMMENDATIONS

➢ *Conclusions*

This study examined the mechanisms and techniques that govern gas drainage in low-permeability coal seams. Drainage performance depends on the complete pathway from gas desorption in the coal matrix to diffusion into the fracture system and flow through connected fractures toward a sealed borehole. Low natural permeability, stress-induced fracture closure, poor borehole connectivity, and air leakage are therefore the principal causes of weak or unstable drainage performance.

The analysis indicates that permeability enhancement should be selected according to the dominant limitation and geological setting. Hydraulic fracturing can enlarge the

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connected drainage volume where confinement and fluid acceptance are suitable. Hydraulic slotting provides local stress relief and increased exposed surface, while controlled blasting can generate fractures rapidly where its higher operational risk is justified and controlled. None of these methods can perform reliably without an appropriate borehole layout, effective sealing, controlled extraction pressure, and sustained monitoring.

The illustrative sensitivity analysis identifies effective permeability and sealing quality as the strongest controls on useful methane recovery. Borehole spacing and drainage time influence the volume of coal treated, whereas extraction pressure has an optimum range beyond which leakage may increase and methane concentration may fall. Performance should be assessed using methane flow, concentration, cumulative recovery, and pressure decline together.

- *Recommendations*

A staged field trial is recommended before mine-wide implementation. The trial should include an untreated control area, document the original gas and stress conditions, and apply one clearly defined enhancement design. Borehole construction, sealing materials, stimulation parameters, and extraction settings should be recorded so that the response can be reproduced and compared.

Monitoring should include gas flow rate, methane concentration, suction pressure, cumulative gas volume, and coal-seam pressure where observation holes are available. Measurements should continue long enough to capture the initial response and subsequent decline. Seal-integrity checks should be conducted whenever total flow increases while methane concentration decreases.

Future research should quantify the sensitivity framework using field data or a calibrated numerical model. Parameter ranges should reflect actual mine conditions, and interactions between permeability, gas pressure, borehole spacing, sealing quality, and extraction pressure should be evaluated. Economic assessment should compare the additional recovered gas and safety benefit with drilling, stimulation, water management, and operating costs.

The final drainage design should prioritise mine safety while supporting methane utilisation and emissions reduction. A technically successful method produces a sustained reduction in residual gas risk, maintains acceptable methane concentration, and can be implemented consistently under the geological and operational conditions of the mine.

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