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Advanced directional drilling technology for gas drainage and exploration in Australian coal mines

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Abstract

With the continuing technology innovation, directional drilling technology has provided the coal mining industry with effective and practical options for pre- and post-drainage and exploration in Australia. In the past thirty years, in-mine borehole steering equipment has been developed from the single shot camera survey systems to the advanced Directional Drill Monitor utilizing Modular Electrically Connected Cable Assembly (DDM-MECCA) survey instruments, which provides rapid and easy underground borehole survey measurements whilst drilling. The presence of coal seam gas such as methane poses a significant safety hazard to underground coal mining all over the world. However, gas can be captured using pre- and post-drainage techniques to improve coal production, energy recovery, enhance safety, environmental mitigation. An additional benefit of directional drilling is geological explorations in advance of mining. As any discontinuities intercepted during in-seam directional drilling, such as faults, folds and igneous intrusions, can be monitored by drilling fluid pressures, changes in thrust, vibration, rate of penetration and inspection of cuttings. Directional drilling technologies offer coal operators a cost effective exploration alternative without speculation. Applications of the directional drilling technologies in Australian coal mines have established the benefits of the methodology for gas control and geological explorations. Directionally drilled flank boreholes provide shielding to the gate entry developments, horizontal goaf boreholes for gas drainage in deep multi-level mines, and hydro fracturing and exploration in advance of mining. However, there still remains four major problems associated with directionally drilling, and these include: sticky drilling in complex conditions, sensitivity of down hole probe, in-hole stability and drill depth capacity.

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Keywords: directional drilling technology; gas drainage; geological exploration; in-seam directional drilling; gas outburst; safe mining

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1. Introduction

In coal mining industry, directional drilling has various applications, including pre-and post-gas drainage, detection of abandoned workings, dewatering, identification of coal discontinuities in advance of mining, determination of coal, roof, and floor characteristics [1, 2]. In-seam directional drilling from underground roadways has essentially grown from the oil industry in the late 1970's, principally for the purpose of gas drainage [3]. There are three main benefits associated with gas drainage, which include the improvement in health and safety for the underground workforce, a decreased environmental impact, and the production of a relatively clean-burning energy source [4]. A project consisting of three long horizontal holes directionally drilled for a Coalbed Methane (CBM) drainage system was initiated in 1976 in the USA [5]. In 1980, the first routine pre-drainage drilling program, ahead of mining commenced at West Cliff Colliery, NSW, Australia [6, 7]. The first directional in-seam longhole was drilled in Australia at Appin Colliery in 1987 to drain gas from the adjacent coal seam located 18 m below the working seam [8]. In 1996 around 120 km of rotary drilling at around AU $30 per metre and 400 km of directional drilling at around AU $60 per metre were drilled respectively. In 1997, the directional drilling distance increased to around 460 km, while the rotary drilling remained at 120 km [9].

Directional drilling can provide many advantages. It provides longer length and more accurate placement of boreholes for improved gas drainage efficiency and longer drainage time; allows the implementation of innovation goaf gas drainage techniques; has ability to steer boreholes to stay in-seam or hit specific targets; promotes a more focused simplified gas collection system; reduces labour intensity; and provides additional geological information (e.g., coal thickness, faults and other anomalies). There is a growing trend towards replacing much of the rotary drilling with directional drilling.

Gas and coal outbursts have been a long-standing potential hazard for underground coal miners in many countries since the mid-nineteenth century. More than 35, 000 outbursts have been noted over the last 150 years [10]. Australia has an identified *in situ* coal resources of 77 Bt, which is the fourth largest coal producer and the largest coal exporter in the world, and the total production from Australian longwall mines during 2010 was 105.8Mt [11]. Coal Mine Gas (CMG) levels need to be reduced to below safe gas content threshold values, which have been set by strict Australian health and safety regulations, before mining can go ahead. In the last decade, outburst risk has been brought under control in Australia by performing directional in-seam gas drainage prior to mine development and production. As shown in Fig. 1 [12], thanks to the application of directional drilling technology and many other advanced mining technologies, Australia has achieved a high standard of safety, high production and efficient exploitation of coal and gas.

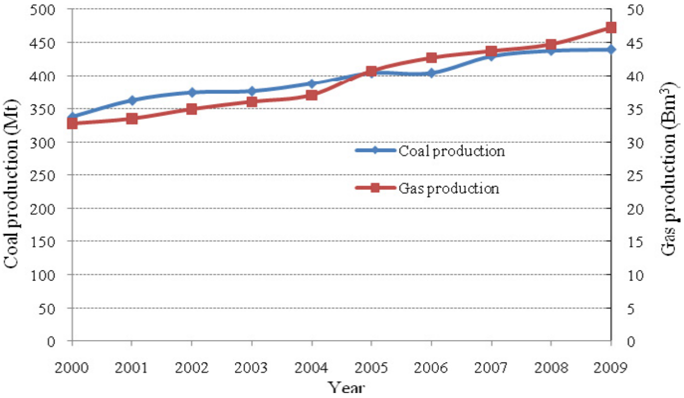

Fig. 1. Production of coal and gas in Australia during 2000-2009 (Source: International Energy Statistics, 2010)

Presently, significant advances in directional drilling systems provide a range of gas drainage options and the ability to better identify and understand geological and mining conditions in advance of mining [13]. The applications of directional drilling technology for gas drainage and geological conditions have also been carried out in North America, Australia, China, Poland, Japan, UK and Russia, with great social and economic benefits [14-17]. The rapid development of directional drilling equipment and related technologies has brought a broad prospect for efficient and safe mining in Australia and beyond.

2. Development of the directional drilling technology

2.1. Advances in directional drilling systems equipment Structure

Directional drilling equipment is comprised of a high thrust permissible drill, a steerable downhole motor assembly, drill rods, drill bits, and a survey system. The Directional Drill Monitor (DDM) is an advanced instrument for real-time in-hole surveying. The length of the directional drilling hole is principally dictated by the capacity of the drill rig. A minimal standard in underground gas drainage and exploration rig would have the following specifications [17]:

a) 75 kW, 1000V hydraulic power unit to power the rig and the water pump,
b) 250 l/min water supply and a 10 MPa high pressure pump,
c) 135 kN thrust and pull,
d) 1500 to 2000 Nm torque, NQ capacity rotation unit,
e) Track mounted, and
f) Compact enough to operate in a roadway and allow vehicles to pass.

A schematic representation of standard practice directional drilling downhole equipment is shown in Fig. 2 [18].

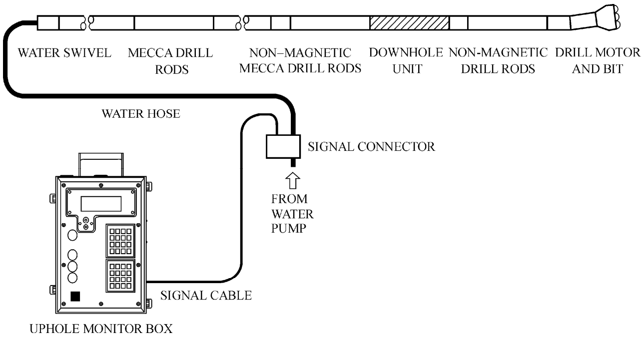

Fig. 2. Directional drilling downhole equipment (Thomson, 1997)

In conjunction with the advances in gas drainage methods there have been significant improvements in drilling technologies, focusing on the need for directional drilling control and holes survey. Recent advances in directional drilling systems have substantially increased drilling rates, depths, and borehole placement accuracy [19]. A prime example is the DDM MECCA, an electronic drill navigation system, equipped with tri-axis geometric sensors and located behind the downhole motor, sends survey information up the drill steel at high baud rates through a modular cable assembly to an uphole control system [6]. The DDM MECCA substantially decreases survey time relative to single shot borehole systems. Depending on the depth of borehole, the single shot process can take up to 45 minutes. With the DDM MECCA, Valley Longwall has achieved a world record directional drilling production rate of 512 m in one shift, and the company-wide annual production rates as high as 183,000 m. With the DDM MECCA, operators have achieved accuracies of better than ±0.5° in azimuth and ±0.1° in pitch, while ±1° in azimuth and ±0.5° in pitch with single shot instruments [8]. New high performance wireline rod with a reverse flank thread design (e.g., Boart Longyear RQ^{TM} product) provides much higher strength without changes in dimension or rod weight compared to the conventional wireline tubing. The configuration of streamlined DDM MECCA embedded with the high performance wireline rod enables the development of boreholes to distances greater than 2000 m.

In general, the development of directional drilling technology for gas drainage and exploration applied in Australia has experienced three main phases as follows:

(1) Early trial phase. From the middle 1980s to 1995, directional drilling in coal commenced in Appin Coal Mine (BHP Coal Holding Pty Ltd) for gas drainage [20], and then tested in other gassy mines. The characteristic in this phase was the use of single shot camera survey systems for borehole steering. Problems associated with these trials include lack of azimuth control, long survey time, limited drill depth, and insufficient reliability.

(2) Development phase. From 1995 to 2002, borehole pitch control stabilizers had been replaced with permissible downhole measurement instrumentation while drilling, high power drilling rigs, high performance water pumps, high torque downhole motors, high penetration bits and precision survey tools [21, 22].

(3) Well-developed and wide application phase. From 2002 to present day, directional drilling technology has matured and well developed, allowing wide applications not only in Australian mines, but also technology transfer to developing countries such as China, India, Russia and South Africa [23]. The widespread application of directional drilling technology has greatly improved the safety and efficiency mining in these countries.

2.2. Advances in gas drainage technique with directional drilling systems

The maximum and average depths of underground coal mining in Australia are 600 and 280 m respectively [8]. The *in situ* gas content of coal seams in deeper operations is between 5-20 m^3/t. The presence of gas within coal seams represents a significant hazard in underground coal mining [24]. Holes of 1000 m or more can be installed using underground directional drilling techniques, thereby increasing the efficiency of degassing. Furthermore, where mines are not too deep, extensive in - seam drilling can be carried out from the surface. Surface to in-seam (SIS) directional drilling techniques have proven to be effective in pre - draining coal seams with a permeability range of approximately 0.5-10 md or less. A combination of pre - and post drainage using advanced, surface - based directional drilling techniques has been implemented in Australia, where total mine emissions can reach 8 m^3/s and longwall capture efficiencies of 80% are required [25, 26]. Australian experiences have shown that the technique of surface to in - seam drilling is superior to underground in - seam drilling. The is because the borehole can be drilled in advance of mining and therefore is less likely to have the time allowed for effective drainage to be shortened by coal production activities. In areas where vertical goaf wells cannot be deployed, and in multi-level mining operations where cross-measure or overlying goaf gas recovery techniques are ineffective or too costly to apply, drillers can directionally steer horizontal goaf boreholes up over future longwall faces. This creates low pressure sinks which can draw goaf gas generated from overlying sources.

Straddle packer was adopted to hydraulically fracture in-seam directionally drilled boreholes to increase hole connectivity to natural fractures and cleats in tight coal seams [13]. The advantages of water-jet assisted gas drainage method has been identified as: (1) increasing gas drainage efficiency; (2) a possible development of a gas drainage fractured network within coal seams associated with panel extraction; and (3) reducing the risk of exceeding gas limits during longwall mining. Some surface vertical holes using the hydro fracturing technique were applied in New South Wales and Queensland.

Longwall mining has significant impact on surrounding strata by breaking up vertical permeability barriers that separate gas bearing formations from workings. Effective goaf gas drainage designs need to consider the stress distribution in the goaf, distance to gas bearing strata, the geomechanical characteristics and the impact of longwall mining upon the strata. Geomechanical characteristics of lithologies are relevant for assessing drillability and borehole stability. Frequency and type of discontinuities, including stress orientations affect borehole stability and dictate permeability anisotropy. With the knowledge of the conditions mentioned above, designers can plan reasonable borehole location and orientations to maximize gas drainage benefits. *In situ* gas content, desorption characteristics, natural fracture and cleat permeability determine the lead time required for in-seam gas drainage and borehole spacing.

3. Directional drilling technologies for gas drainage

3.1. Directional drilling technology for pre-drainage

Gas drainage prior to mining is the most common method presently being used in Australian coal mines, and directional drilling from the surface presents an attractive option [5]. As the drainage efficiency depends mainly on the permeability of the coal seam, current practice is primarily focused on shallow deposits as in Australia [27]. In Queensland, there are number of relatively shallow mines (150-300 m), where gas pre-drainage has been undertaken from surface by borehole directional drilling. In divorcing gas production from the mine operation, costs can be kept down through wide spaced drilling and long lead time.

1) Directional holes drilled from the surface

Surface to in-seam (SIS), medium radius drilled (MRD) is most commonly applied at relatively shallow depths (200-400 m) [28]. MRD wells have the following advantages over other forms of drilling [3]:

- Relatively high production from low permeability coal due to the high level of contact via the long, directional in-seam boreholes,
- High gas recovery (e.g. 80%) resulting from accurate drilling to a predetermined pattern, and
- Higher purity gas and improved stability of gas drainage boreholes during both drilling and drainage due to drilling above gas desorption pressure.

Surface to inseam horizontal drainage drilling is shown in Fig. 3.

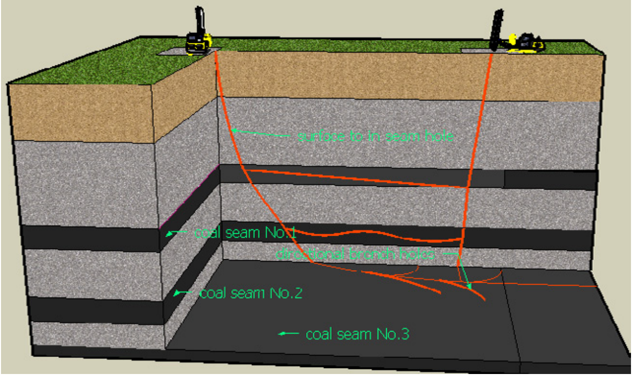

Fig.3. Surface to inseam horizontal drainage drilling technologies

Adoption of MRD for surface pre-drainage of coal seams has allowed drainage lead time in excess of three years. The use of surface well sites with multiple directional wells drilled and produced will minimize environmental impact and will lower costs [29]. SIS drilling technology in Australia, employing a typical bend radius of 250-350 m, has seen widespread application, particularly in the Queensland CBM industry [30]. MRD is now becoming a favoured method for pre-drainage programs in many Queensland coal mines with increasing applications in the Hunter Valley and Illawarra region, NSW.

2) Horizontal longholes

Horizontal directional drilling is the most effective in advance degasification of highly permeable coal seams [31-33]. This drainage technique typically involves drilling long horizontal holes from gateroads into overlying strata of the panel for goaf gas capture near the face during retreat operations. Horizontal placement of the boreholes varied from 0 to 100 m from the gateroads and vertical placement varied between 0 and 20 m above the working section. Fig. 4 shows the typical layout of the horizontal holes in a longwall. Average gas flow from these holes was around 30 to 50 l/s. Analysis of the results showed that horizontal holes drilled at 8 to 11 m above the working section produced relatively more gas with less air dilution.

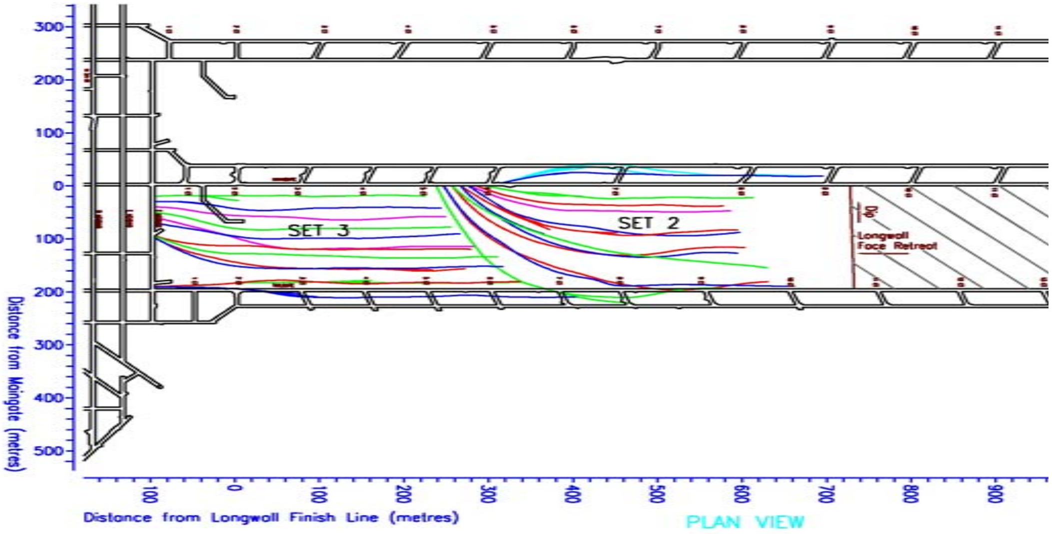

Fig. 4. A typical location and plan of horizontal holes in a longwall panel

3.2. Directional drilling technology for post-drainage

(1) Post-drainage by directional holes drilled from the surface

In situations where significant surface access restrictions exist, vertical well surface goaf drainage could not be employed to manage high gas emissions. In such cases, a good alternative method is the use of radius drilling, positioned on the tailgate side, approximately 30-50 m above the roof of the mining seam, drilled ahead of the retreating longwall face. Fig. 5 illustrates the method of vertical and horizontal goaf drainage well typically employed [26].

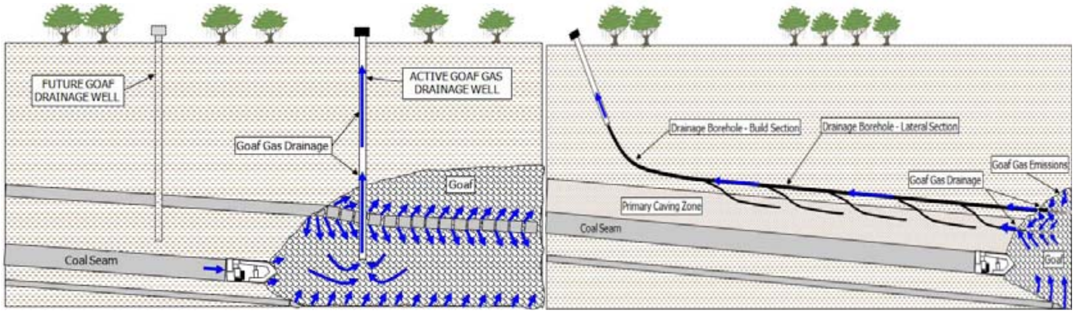

Fig. 5. Vertical and horizontal well surface-based goaf gas drainage (Black and Aziz, 2009). (a) Vertical well; (b) Horizontal well.

According to the nature of goaf formation, the position of the open end of the horizontal drainage borehole can be expected to remain relatively constant throughout the operating life of the well, resulting in a stable and overall greater gas production capacity than that which is achievable through the use of vertical goaf drainage wells. A further advantage is that multiple laterals can be branched out to form multiple connections to the goaf, which improves both redundancy and overall gas production capability, as shown in Fig.5(b).

(2) Post-drainage of old or active goaf areas from underground

There have been many methods used to drain gas from both the active and sealed goaf: cross-measure boreholes, back-of-block drainage, goaf seal drainage and horizontal directional drilling. Many of Australian mines exploit coals with high *in situ* gas contents (greater than 20 m^3/t) and low permeability (less than 1 md) [26]. Because of the presence of overlying and underlying gas bearing strata, these mines have encountered high goaf gas emissions during longwall mining. In this case, directional drilling can provide a cost effective alternative. Drillers can develop directional horizontal goaf boreholes in advance of longwall mining up over the coal seam from the mining level. These boreholes target areas below the nearest overlying gas source seam and are placed in the fracture zone, above the rubble zone of the goaf.

3.3. Gas drainage cost analysis

Gas drainage system costs depend on various factors (e.g., equipment, labour, surface access) and vary substantially from country to country. These cost differences are compounded by variations due to geological and mining conditions within individual countries and therefore generalization inevitably leads to wide ranges. Table 1 lists a relative cost comparison of gas drainage methods per tonne of coal produced (2009 prices). The basis for comparison is the drainage of a notional, gassy, longwall panel 2 km long and 250 m wide at 600 m depth with a 3 m thick seam and extraction rates of 2.0 Mt/a to 0.5 Mt/a benchmarked using data from Australia [25].

The drainage method selected must be suitable for the selected mining and geological situation. Costs for surface - based methods increase with depth of working. In very gassy mines, a combination of various drilling methods may be required before high coal - production rates can be safely achieved. The costs of drainage systems increase with geological complexity. An estimated typical operational cost range, for extracting CMM from underground on a pure methane basis, between US \$0.06/m^3 to US \$0.24/m^3 [34]. An effective methane drainage program can reduce methane emissions significantly, thereby improving safety conditions in the mine, it also has the potential for increasing mining productivity, and the recovered gas be used as valuable energy resources.

Table 1． Relative Costs per ton of various gas drainage methods (Source: ECE Energy Series No. 31, 2010)

Method	Basic Technology	Major Cost Items	Major Cost Variables	Estimated Cost (US $/t)
Underground pre－drainage	Directional longholes, in－seam along panel length	Specialist drillers and equipment	Borehole diameter and length	0.4-3.2
	Rotary-drilled boreholes across the panel	Rotary drilling rig and equipment	Borehole diameter and length	0.6-4.0
Surface pre-drainage	Vertical well with conventional fracture stimulation	Contract drilling, casing and facing services; sealing on abandonment	Borehole depth and number of seams to be completed	1.2-9.6
	Surface to in-seam well with multiple laterals	Contract drilling, casing and specialized, directional drilling services; sealing on abandonment	Borehole depth and total length of in-seam laterals drilled; cost can escalate rapidly where drilling difficulties arise	1.0-8.0
Underground post-drainage	Cross-measure boreholes (from existing roadways)	Rotary drilling rig and equipment	Borehole diameter and length	0.1-1.6
	Drainage galleries	Additional roadway development	Distance above/below worked seam and roadway dimension	0.3-11.2
	Super-adjacent (or sub-adjacent) boreholes or guided horizontal boreholes	Specialist driller and steered down-hole drilling equipment	Drilling difficulty for the radius bend	0.5-4.0
Surface post-drainage	Goaf boreholes	Contract drilling and casing; sealing on abandonment	Depth	1.4-15.2

4. Geological explorations

The majority of directional drilling is conducted to drain gas. However, an increasing amount of drilling is directed at identification of seam structure, probing of discontinuities and verification of abandoned working location [13]. In essence, by drilling into and following along coal seams, it is possible to obtain more accurate delineation of the coal seams than was previously possible from conventional exploration methods [31]. Directionally drilled longholes for exploration have been utilised at FAI Mining collieries in Australia since 1986. The longest inseam hole drilled was 1018 m and cores have been taken from up to 1002 m [35].

4.1. Identifying Seam Structure

Plotting the profile of the borehole from downhole surveys and driller logs provides the mining operation with an indication of coal seam structure. With downhole motor drilling, the more powerful drill rigs allow drilling through smaller structures without bogging. Directional drilling provides benefits in investigating possible geological structures. The ability to navigate the drill string, deviating left, right, up or down, enables a competent operator to explore the strike, magnitude and nature of geological bodies in a way that is simply not possible utilizing conventional rotary drilling. In the latter case mis-interpretation of structures as normal floor or roof material has resulted in some extremely costly planning errors that have had a disastrous effect on mine productivity.

4.2. Probing for discontinuities

Any discontinuities intercepted during drilling, such as faults, folds and igneous intrusions, are detected by monitoring drilling fluid pressures, changes in thrust, vibration, rate of penetration, and inspection of cuttings. Because of the high placement accuracy achieved with the DDM-MECCA, particularly in profile, directional drilling can determine the thickness of coal seams and normal fault displacements with reasonable precision.

4.3. Verifying the location of abandoned workings

Mining regions have incomplete archives and cannot accurately specify the location of old mining workings. Modern mining operations must navigate away from these potentially water-filled or gas-filled workings. Many experiments have been successfully carried out in Australia through directional drilling at frequent intervals from developments to ensure that the new workings are driven sufficiently away from the abandoned ones.

4.4. Coring and geophysical logging

Mine geologists have correlated roof stability and rockburst conditions with immediate roof composition. The coring program involves drilling multiple tangential boreholes from inseam, up into the roof and down into the floor. The innovative motor-core system retrieves intact coal and roof cores up to 3 m in length from directionally drilled boreholes for geological inspection. To date, the in-seam directional drilling exploration program has provided invaluable information in advance of mining, and at substantially lower costs than a comparable barge deployed vertical drilling program.

5. Problems and prospects

5.1. Problems existed

(1) Sticky drilling

During the 1980’s, several drainage holes directionally drilled across the block bogged in a longwall mine [21]. Generally, sticky drilling is normally associated with increased friction due to cuttings accumulation and geological structures such as faults and structures that have formed stress concentrations. When drilling through these structures drill rods tend to bog, which results in poor cutting due to slow rotation speeds. In the worst case, bogging can cause loss of equipment due to uncoupling of drill strings and has resulted in thousands of dollars of drilling equipment to be left down boreholes due to failed salvage attempts. Despite vast research into sticky drilling, it is still relatively unknown what causes the rods to bog.

(2) Sensitivity of down hole probe

There is still much to be done to improve the collection of data from the hole for identification of geological structures and reporting of the data. Boreholes drill a significant percentage of redundant metres trying to stay inseam, each branch also increases the risk of a failed borehole. The development of down hole probes for the detection of structures while drilling has been frustratingly slow.

(3) In-hole stability

Difficult to drill areas of mines are often encountered in inseam directional drilling. Limitations are primarily due to in-hole stability: drilling in soft or highly sheared coal, soft dykes, frequency and type of geologic discontinuities and high stress and high gas.

(4) Depth capacity

Currently, depth capacity is limited by the problems of in-hole friction and associated surging feed rates [36]. These spikes in the torque loading at the bit may result in stalling of the down-hole motor and subsequent lack of progress in the hole.

5.2. Prospects forecast

(1) In-seam borehole for shielding gate entry developments

In-seam boreholes have a significant impact on the development of gate entries in advance of mining. Because of high cleat and natural fracture permeability, in-seam boreholes rapidly shield gate entry development activity from gas emissions and allow significant increases in coal production.

(2) Horizontal gob boreholes for deep multi-level mines

Coal exploitation is conducted at deep mining levels (greater than 700 m) using multi-level mining techniques. Many of these operations exploit coals with high *in situ* gas contents and low permeability (between 0.1-1 md). Because of the presence of overlying and underlying gas bearing strata, mines are required to drill multiple goaf boreholes to control gas.

(3) Hydraulically fracturing directionally drilled boreholes

Hydro-fracturing has been developed as a solution to low permeability coal and works by using high pressure water as a medium to fracture virgin coal in order to improve permeability. Pre-splitting blasting is another potential application for de-stressing and increasing permeability and reducing requirements for mining in hard coals. In Australia, hydro-fracturing has mainly been adopted in pre-drainage where the *in situ* stress on the coal has resulted in poor permeability.

(4) Exploration in advance of mining

The ability to control boreholes at great distances (beyond 2000 m in the near future) with high accuracy makes directional drilling invaluable for coal mining exploration projects. There is a promising future of directional drilling technology to verify the location of abandoned workings, drain water from an active mine into the rich watershed, identify the seam structure and discontinuities, and core and geophysical log and characterize coal seam structure with advanced prospecting instruments.

6. Conclusions

There have been significant improvements focusing on the directional drilling control and survey systems. In-mine borehole steering equipment has developed from single shot camera survey systems to DDM-MECCA survey instruments with high power drilling rigs, high performance water pumps, high torque downhole motors, high penetration bits and precision survey tools.

In-mine directional drilling technology has been used in Australia for gas drainage and exploration purposes. These include surface to in-seam holes, horizontal directional drilling holes, in-seam pre-drainage holes, cross measure boreholes, post-drainage from the surface and old or active goaf areas from underground. Australia has benefited significantly from the directional drilling technology for gas control and geological explorations especially in gassy and complicated coal mines.

Nevertheless, field applications of directional drilling have also encountered a number of challenges and limitations; these include sticky drilling, sensitivity of down-hole probe, in-hole stability and limited depth capacity. With the improvement of drilling capability and accuracy, this technology will be widely for shielding gate entry developments, horizontal gob boreholes for deep multi-level mines, directionally drilled hydraulically fracturing boreholes and geological explorations in advance of mining.

Acknowledgments

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