Drill rig characteristics and drilling techniques required for maximum borehole depth with directional drilling

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ABSTRACT: Directional drilling has been the established form of in-seam drilling for gas drainage, exploration and water management for the past three decades. Although there has been a desire to achieve longer boreholes to depths similar to that achieved with surface drilling, seam conditions, equipment capacity and drilling methods have limited in-seam drilling depths. Development into a new area of Metropolitan Colliery required boreholes to depths of 2000 m to provide the required gas drainage. This offered an opportunity to use a combination of slide and rotary drilling similar to that used with Surface to Inseam (SIS) drilling to achieve the required depths. This paper presents the results of the drilling, describes the drilling techniques used and defines the equipment specifications required for undertaking a range of in-seam directional drilling projects.

INTRODUCTION

Directional drilling in coal mining has been developed to a stage where standard practices allow boreholes to 1400 m to be drilled regularly in slide drilling mode with the occasional borehole being drilled to beyond 1700 m. The record depth for inseam boreholes was 1761 m in 2002 in Australia (Valley Longwall, 2002). To extend the depth to 2000 m, a combination of directional slide and rotary drilling was planned to be applied from the start. Slide drilling mode involves feeding the Down Hole Motor (DHM) into a borehole with “flip-flopping” orientations to provide directional control while with rotary drilling mode; the drill string is rotated over extended lengths while the desired trajectory and alignment are maintained.

Metropolitan Colliery is developing in the Bulli seam into a new area which has high gas content; carbon dioxide being the dominant seam gas. Limited access did not allow the standard gas drainage drilling program to be employed to drain the gas prior to mining. With the proposed gate-roads 2000 m long, the colliery approached VLI to attempt drilling long, in-seam boreholes to 2000 m and beyond to provide drainage coverage since drilling shorter holes would necessitate a staged and disrupted development to allow a progressive cycle of drilling and gas drainage. Directional drilling practices incorporating both slide and rotary drilling were developed (Hungerford and Green, 2016) with comprehensive data recording was employed to allow analysis of drilling performance.

This paper presents the results of the successful completion of that drilling and defines the key elements of equipment specifications required for the directional drilling of longer boreholes.

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DEPTH LIMITATIONS

As in-seam directional drilling was being developed in Australia in the late 1980's, the standard NQ sized configuration used a 73 mm diameter DHM fitted with a 1° bend to drill an 89 mm diameter borehole. Directional control was achieved by repeated “flip-flopping” of the alignment of the DHM bend; usually at 6m intervals. The feed pressure provided by the drill rig started surging beyond 60 m so the feed rate was progressively reduced to prevent stalling of the DHM as borehole depths increased (Hungerford, et al, 1988). Eventually surging and the resultant stalling caused the termination of drilling with 1005m being the longest borehole achieved.

Larger diameter drilling using a higher torque capacity DHM was proposed to reduce the effects of in-hole friction. A 2-7/8” Accu-dril DHM was offered to the industry in 1992 through Asahi (Walsh and Hungerford, 1993.). This unit had a non-magnetic, high-torque, low-speed 4-5 lobe motor section (Hungerford, 1995) which, when fitted with a 1.25° bend and combined with a 96.1 mm diameter Poly Crystalline Diamond (PCD) drill bit, greatly reduced surging with drilling rates and depths improved. In 1993 and 1994, the first two boreholes drilled with this configuration achieved lengths of 1233 m and 1535 m (Walsh and Hungerford, 1993). This configuration was established as a standard for in-seam directional drilling in Australia and eventually the world. The deflection provided vertical control through a variety of seam conditions while also allowing adequate lateral deviation to achieve curved borehole layouts.

With the higher thrust loading involved, the capacity of in-hole equipment was going to be tested. Analysis of drilling data collected from long-holes (with torque/drag models established) showed the NQ drill rod strength was adequate for the depths being achieved (Gray, 1991), but the suggestion was that borehole depths would eventually be limited due to helical buckling with the current drilling techniques (Gray, 1992). Tests of rod strength had proven that the preferred drill rod joint classed as CHD76 being adopted by the industry was the superior rod in strength and ease of handling in jointing (Gray and Daniel, 2000). Table 1 gives a comparison of torque capacities and the torque of the larger CHD90 rods. Withdrawal friction and rotational torque were also thought to be possible limiting factors from these analyses.

<table>
<thead>
<tr>
<th>Rod</th>
<th>Diameter (m)</th>
<th>Weight - 3m (kg)</th>
<th>Max Torque Rating (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NQ</td>
<td>69.9</td>
<td>23.4</td>
<td>750</td>
</tr>
<tr>
<td>CHD76</td>
<td>69.9</td>
<td>24.5</td>
<td>2430</td>
</tr>
<tr>
<td>CHD90</td>
<td>88.9</td>
<td>36.3</td>
<td>3150</td>
</tr>
</tbody>
</table>

The maximum borehole depths being achieved varied without apparent changes in drilling practices or conditions but comprehension recording of drilling data allowed trends to be established (Hungerford, et al, 2012):

- The thrust required in all boreholes started increasing more rapidly as significant depths were reached (Figure 1).
- The maximum thrust capacity of the drill rig was not usually reached before drilling was terminated due to stalling of the DHM.
- Altering the orientation of the DHM at 3m intervals as shown in Borehole MG40-30-1 (Figure 1) greatly reduced the depth achieved.
- Boreholes with substantial lateral curves early achieved equivalent or greater borehole depths.
It was established that as the axial loading through the rods increased, the rods were being flexed through the regular left/right curves created by the “flop/flop” directional drilling and forced into the outside walls of curves in the boreholes. With axial loading greatest in the rods closest to the collar of the borehole, the nature of the curves early in the borehole had greatest effect on the borehole friction. And as this friction is overcome to start moving the rods in the borehole, the rods surge forward driving the bit into the face to create a torque loading spike which tends to stall the DHM. Even with high enough thrust capacity, the rig can’t feed the DHM into the face at a consistent rate that avoids stalling.

![Figure 1: Thrust loading in directional drill boreholes with 6m and 3m orientation changes](image)

**Surveying**

The survey systems were thought to be a limiting factor with some signal problems being experienced previously when drilling boreholes beyond 1500m. Subsequent development of the Drilling Guidance System (DGS) (McCabe and Hellyer, 2013) had apparently improved signal strength and transmission but this had yet to be proved over the greater depths.

**Rig capacity**

The initial drill supplied for the project was a modular VLI Series 1000. This drill rig had a thrust capacity of 104.6 kN (compared to 140 kN of the track mounted Series 1000) and a torque capacity of 2430 Nm. The lesser thrust capacity was thought to be a possible limitation in achieving 2000 m when compared to the 220 kN capacity of the Fletcher LHD used previously for the record drilling to 1761 m.

**Drilling practice**

Since it was known that borehole depths were going to be limited to only 1500m with conventional slide drilling, a version of rotary/slide drilling was proposed. The method of drilling termed “Production Drilling” is commonly used by SIS drilling and previously in some shorter underground drilling operations (Eade, 2002).
Before drilling commenced, the drillers were instructed on the drilling practices required for the project. Most drillers had used rotary/slide for short sections of drilling on previous projects so were comfortable with adopting the practice. The initial drilling parameters included:

- Slide drilling to establish position and dip within the seam and on alignment/azimuth.
- Slide drilling to maintain lateral borehole curve to maintain horizontal positioning of the borehole (follow the flight path).
- Slide drilling to target the seam roof for seam profile definition.
- Slide drilling to establish each subsequent branch.
- 200 litres/min water flow to operate the DHM.
- Rotary drilling whenever possible when comfortably on line.
- Rotary drilling at 30 – 60 rpm to limit damage and wear to the DHM.
- Record usual drilling parameters of thrust and hold-back hydraulic pressures and water idle and drilling pressures.
  - Record main hydraulic pump pressure when rotary drilling.
  - Survey at 6 m intervals and also record each 3 m intermediate survey.
- Avoid short interval orientation changes when slide drilling.

The project was undertaken operating with two man shifts (a driller and one off-sider) of eight hour duration at the site. This allowed the drilling of each borehole to continue without regular significant delays.

Drilling configuration

The DPI equivalent of the non-magnetic 4/5 Accu-Dril DHM was used with a 1.125\(^\circ\) bent housing fitted with a 1 mm thick wear pad. A standard Asahi 96.1 mm diameter PCD bit was used which combined for an off-set at the bit (B) in Figure 2 (Hungerford and Green, 2016) of 6.7 mm. This was equivalent to being fitted with a bent housing of 1.22\(^\circ\). When initially rotating the DHM, the heel of the bend would be flexed 2.9 mm to fit within the 96.1 mm diameter until either the hole diameter was increased by the rotation or a straighter section of borehole is created.

After the first hole, the bit size was increased to 99 mm by moving the outer cutters outward. This reduced the offset at the bit (B) to 5.3 mm and thus reduced the effective bend to 1.12\(^\circ\). In rotating the DHM, the heel of the bend fitted within the 99 mm diameter and avoided any forced flexing of the DHM.

![Figure 2: Deflection of DHM (A) and bit (B) with wear pad](image)

Drilling Conditions

Ultimately, drilling conditions have an influence on the borehole depths achieved. Good intact coal conditions allow for easy directional drilling with DHMs with minimal problems of in-hole collapse and bogging. If any unstable conditions are experienced, ongoing drilling beyond that point would always be suspect with loss of expensive equipment being the main concern. Drilling to extreme depths beyond the 600-700 m over-coring capacity eliminates over-coring recovery as insurance and plans need to be in place to eventually recover the equipment when intersected by mining. The Bulli seam has an average thickness of 3.0 m with no geological structures expected in the area of the proposed drilling.
Drilling results

The details of the eleven boreholes were completed from two drill sites are shown in Table 2 in the sequence of drilling. All boreholes were drilled with a combination of slide and rotary drilling with each borehole having different applications of rotary drilling, off-set entry angle and eventual lateral deviation. That delivered a different depth in each borehole from which slide drilling could no longer continue and drilling was continued with rotary drilling only. The table indicates the depth to which slide drilling was possible, the lateral deviation and the reason for terminating each borehole. The first borehole (EX03) which was used as an exploration borehole to define the seam profile involved more roof intersections and subsequent branching and more metres drilled. Most boreholes were completed with average drilling rates above 100 m/shift.

Table 2: Borehole Data

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Depth (m)</th>
<th>Total Drilling (m)</th>
<th>Slide to (m)</th>
<th>Lat Dev (m)</th>
<th>Shifts</th>
<th>Drilling Rate (m/shift)</th>
<th>Terminated</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX03</td>
<td>1779</td>
<td>2775</td>
<td>1746</td>
<td>116 L</td>
<td>33</td>
<td>84.1</td>
<td>No signal</td>
</tr>
<tr>
<td>EX02</td>
<td>1875</td>
<td>2124</td>
<td>1851</td>
<td>58 L</td>
<td>16</td>
<td>132.7</td>
<td>Floor</td>
</tr>
<tr>
<td>DH01</td>
<td>1971</td>
<td>2205</td>
<td>1803</td>
<td>31 L</td>
<td>17</td>
<td>129.7</td>
<td>Floor</td>
</tr>
<tr>
<td>DH04</td>
<td>2001</td>
<td>2196</td>
<td>1821</td>
<td>129 L</td>
<td>17</td>
<td>129.2</td>
<td>Roof</td>
</tr>
<tr>
<td>DH05</td>
<td>2007</td>
<td>2568</td>
<td>1653</td>
<td>78 R</td>
<td>28</td>
<td>91.7</td>
<td>To design</td>
</tr>
<tr>
<td>DH08</td>
<td>2151</td>
<td>2568</td>
<td>1743</td>
<td>40 L</td>
<td>20</td>
<td>128.4</td>
<td>No rods</td>
</tr>
<tr>
<td>DH09</td>
<td>2103</td>
<td>2451</td>
<td>1761</td>
<td>83 L</td>
<td>21</td>
<td>116.7</td>
<td>No rods</td>
</tr>
<tr>
<td>DH10</td>
<td>2007</td>
<td>2610</td>
<td>1761</td>
<td>121 L</td>
<td>26</td>
<td>100.4</td>
<td>To design</td>
</tr>
<tr>
<td>DH11</td>
<td>2016</td>
<td>2451</td>
<td>1920</td>
<td>166 L</td>
<td>21</td>
<td>116.7</td>
<td>No rods</td>
</tr>
<tr>
<td>DH06</td>
<td>2007</td>
<td>2154</td>
<td>1923</td>
<td>145 R</td>
<td>21</td>
<td>102.6</td>
<td>To design</td>
</tr>
<tr>
<td>DH07</td>
<td>2013</td>
<td>2184</td>
<td>1884</td>
<td>0 L/R</td>
<td>18</td>
<td>121.3</td>
<td>To design</td>
</tr>
</tbody>
</table>

Figure 3 has the eleven boreholes plotted on the mine plan showing the proposed gate-road development. Drilling conditions were found to be stable with no structures or boggy conditions experienced.

With little geological and RL information in the area of the proposed drilling, the initial borehole (EX03) served as an exploration hole with regular roof intersections to define the seam profile. This borehole was terminated at 1716 m, which had established a new world record for underground drilling.

Each subsequent borehole increased that record until DH08 established the world record at 2151 m (Table 2). Being the first borehole from the 9 c/t site, regular roof intersections were completed for seam profile definition (Figure 4). The borehole was drilled with a combination of slide and rotary out to 1743 m (Table 2, Figure 5); at which point 45% had been slide mode with 55% rotary. The remainder of the borehole was drilled in rotary mode.
Figure 3: Plan of longhole coverage of proposed gate-roads

Figure 4: Seam and borehole DH08 profile

Figure 5: Drilling mode – slide and rotary drilling
Because of limited access, the boreholes could not be designed as straight holes along their target azimuth with a zero lateral deviation. They were designed with off-set angles and lateral curves to provide the required drainage coverage and not set up specifically to create depth records. The lateral deviations are plotted for the boreholes from the two sites (Figures 6 and 7).

The plot of thrust on the drill string for slide drilling (Figure 8) displays the usual trend of increased drilling rate increase with depth, indicating the increased friction effect of curves earlier in the borehole (Hungerford, et al, 2012). This trend extrapolated to 140 kN thrust indicated the greater capacity track mounted Series 1000 rig would possibly have managed slide mode drilling to 1850 m in this borehole if surging didn’t stop drilling beforehand.

In rotary drilling mode, in-hole friction is greatly reduced (Figure 8) and only starts to increase gradually from the 1400 m depth.

![Figure 6: Lateral deviation of boreholes from 6c/t site](image1)

![Figure 7: Lateral deviation of boreholes from 9c/t site](image2)
Figure 8: Thrust loading in slide and rotary drilling modes

As the trend data from more boreholes are added to the thrust graph (Figure 9), it becomes apparent that the rapid increases in thrust later in each borehole are relatively consistent. The depth at which the rapid increases begin seems to correspond with thrust in the 50-60 kN range with the rate at which that thrust is achieved determining the final depth achieved. The friction due to curves early in each borehole influences the rate of increase in thrust loading and at a thrust loading of 50 kN, the rods are starting to be flexed and driven laterally into the outer sides of each alternate curve in the borehole.

Slide drilling was terminated in all boreholes drilled with the modular rig due to the maximum thrust capacity of 104.6 kN being reached. Slide drilling in the last three boreholes using the higher capacity 140 kN track rig was terminated due to surging feed well under the maximum thrust capacity.

Borehole DH11 was the most successful with depth drilled before slide drilling could not continue. This borehole had the greatest initial off-set angle to the target azimuth and the largest lateral deviation of 166 m to the left. The percentage of slide drilling did not differ appreciably from other boreholes but it was noted that all drilling from 60m to 600m was either slide drilling to the right or rotary drilling.

Figure 9: Thrust loading trends
The reduction in friction provided by rotating the drill rods also provided consistent feed at the bit compared to the surging feed experienced in slide mode. With consistent loading on the bit, drilling rates are more consistent over depth (Figure 10) compared to the rapid reduction in the slide drilling rate to avoid stalling the DHM. The rapid decline of drilling rate corresponded with the rapid increase in thrust loading.

Although the thrust loading was approximately 25% capacity while rotary drilling, the rotational torque loading (Figure 11) was at approximately 70% capacity at depths of 2000 m. The increase in torque loading was relatively linear with increase in depth so apparently not influenced by the extent and magnitude of deviations in the boreholes. At the limit of directional (slide) drilling (1800m), only 62% of the torque capacity was employed. An extrapolation of the trend has the maximum torque capacity reached at 2800 m.

The drilling used 200 litres/min water flow to assess the progressive increase of pressure with depth and identify any potential problems of water pressure capacity. From Figure 12, the idle...
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pressure increased from 1.5 MPa (at the start) at a rate of 0.15 MPa/100 m. The drilling pressure decreased gradually over the depth of the borehole as drilling rates decreased.

Although the idle pressure was more than 2 MPa below the maximum available pump pressure at depths beyond 2000 m, some problems were encountered when starting the DHM. Water pump capacity would likely be the limiting factor of rotary depth capacity of the drilling system.

![Figure 12: Drilling water pressure](image)

The vertical and lateral deviations over each 3 m interval were plotted for both slide and rotary drilling (Figure 13). The rotary drilling did not create straight sections of borehole but the deviations were reduced as seen by the tighter grouping in Figure 13.

![Figure 13: Deviation of slide and rotary drilling per 3 m intervals](image)

Although the drillers were limited to rotational speeds below 60 rpm in the pre-drilling instructions, the drillers experimented with traditional rotary drilling variations of increased rotational speed (to 180 rpm) and reduced drilling rate to curve the borehole downwards. Conversely, they reduced rotational speed and increased drilling rate to curve the borehole
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upwards. This was used successfully to extend all boreholes past the no slide depth. The most effective was in borehole DH08 with an additional 408 m being drilled with rotary drilling to the final depth of 2151 m (Table 1) after slide drilling was no longer possible.

The drillers noticed that they had some lateral control with the vertical control parameters. They believed climbing parameters deflected the borehole to the right and dropping parameters deflected the borehole to the left.

CONCLUSIONS

Conventional directional drilling only with N sized rods and 73 mm DHM will always be limited to depths of approximately 1500 m due to the effects of in-hole friction.

Significant increase in bit diameter and matching DHM deflection with the current system may change the friction dynamics enough to extend the directional drilling depth capabilities to and beyond 2000m.

The combination of slide and rotary drilling with a DHM can extend the directional drilling capacity to approximately 1900 m but increasing the thrust capacity of drill rigs will not overcome the surging which ultimately limits the maximum depth of all directional drilling. Extending drilling past the depth to which directional drilling is possible can only be classed as rotary drilling – slide drilling for directional control is no longer possible.

DHMs must always be provided with enough deflection to provide directional control both vertically and laterally. Reducing the deflection to provide just enough vertical control may not provide enough lateral deviation to follow flights plans with significant lateral off-set. The increased clearance provided by the bit size and DHM deflection for steering also results in significantly more deflection when rotary drilling than is experienced by low clearance core drilling. As such, rotary drilling with a DHM will always produce some deflections in the borehole contributing to increased friction and eventual surging.

DHMs with higher torque capacity can be used to reduce the susceptibility to stalling.

The VLI Series 1000 drill rig was essentially designed as a 1000 m capacity directional drilling rig for the Chinese underground drilling market. But the drilling parameters defined by this project have shown:

- With the 104.6 kN thrust capacity of the modular Series 1000 drill rig, directional drilling can reach depths of 1700-1800m before the maximum thrust capacity is reached.
- With the 140 kN thrust capacity of the track mounted Series 1000 drill rig, drilling depths can be extended until surging causes the termination of directional drilling. The maximum thrust capacity of the drill rig has not been utilised.
- The hydraulics of the rotation system is set at a maximum of 23 MPa (of the 29 MPa available) to provide a maximum torque of 2430 Nm. This torque is listed as the maximum working torque of the CHD76 rods (Table 1) and the maximum recommended pre-torque to which the rod joints should be tightened. Rotary drilling utilised only 1500 Nm (62% of maximum) at the 1800m depth to which directional drilling was regularly achieved.
- The higher rotation torque in reverse could be provided to separate tight rod joints.

In defining the capacity of a directional drill rig, the three key characteristics that must be considered are:

- Thrust capacity to provide the maximum thrust required for the size of directional drilling,
- Rotational torque capacity to match the maximum operating torque capacity of the rods being used, and
- Water pump flow and pressure capacities to suit the DHM being used.
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The specifications of the Series 1000 drill rigs have been shown to be sufficient (with some margin) to manage longhole directional drilling projects. Any increase in capacity of drill rig for N sized directional drilling is unwarranted and will not extend the depths beyond what is achievable.

REFERENCES


