Highwall Slope Stabilisation by the Softwall Method

I.J. Kelso  
Thiess Pty Ltd, Brisbane, Australia

Abstract

Open pit strip coal mining requires a reliable highwall slope design for a safe and economic large-scale bulk mining process. When slope stability issues arise a flexible approach to mine design based on geotechnical analysis is used to assist the operation to manage geotechnical hazards.

Highwall slope instability related to large pit-ward dipping thrust faults occurred in a large strip coal mine in the Bowen Basin, Queensland. The ability to identify the location of thrusts and predict potential instability proved difficult. A series of highwall instability events developed into a 700m-long tension crack located 80m from the crest, resulting in a large block of the highwall creeping towards the active open pit workings. The risk of further highwall instability was high with the potential for premature closure of the pit and loss of significant coal reserves at a time of high global demand for quality coking coal. The geotechnical setting, the failure mechanism identified by detailed geotechnical investigation and the geotechnical engineering approach to managing risk associated with this issue while continuing mining operations are described.

The softwall method comprises a highwall slope design where the rock mass is blasted beyond the pit limit to disrupt rock defects. The softwall design was successfully adopted as the preferred geotechnical slope design to manage potential highwall instability in the final mining strip for the pit. The economic benefit compared to the conventional hard excavated highwall was also evaluated. This further demonstrated the softwall to be an appropriate slope design method for geotechnical risk management for large scale coal mining operations.

1 Introduction

The Bowen Basin in central Queensland is a large Permian – Triassic age sedimentary basin containing world class coking and thermal coal deposits comprising 41 open pit and 13 underground longwall mines producing around 190 million tonnes in 2010 for domestic and export markets (Deedi, 2010). This paper describes a case study involving highwall instability which occurred in a coal mine in the Bowen Basin and the following geotechnical analysis resulting in change to the highwall slope design. The ensuing slope design change is based on the desire to minimise geotechnical risk whilst complete mining the remaining coal reserve.

The exposed Bowen Basin is a 600 x 225 km triangular shaped area in central Queensland, and is known to extend south below Mesozoic sediments and link into the Sydney-Gunnedah Basins. The thick coal accumulation range from Early to Late Permian age and throughout the Bowen Basin coal rank and quality are strongly influenced by the depositional environment, tectonic and syn-sedimentary volcanic activity (Mutton, 2003).

The open pit highwall case study describes a sequence of highwall instability events that developed over a 6 month period into a 700m long by 50m wide block of the highwall creeping towards the active open pit workings. The geotechnical setting, the identified failure mechanisms, and the geotechnical engineering approach towards managing this issue whilst undertaking open pit mining are described.

Excavator-truck mining methods are used in this particular 2.3km long open pit to extract two 6m thick coking coal seams. The northern segment of the pit comprises cast blasting and the southern segment where the seam dip increases pit development occurs in a series of terraces along strike. The overburden is removed on 4m flitches and trucked to lowwall and in-pit dumps.
2 Geotechnical conditions

The local geological setting influence the geotechnical conditions for open pit mining. Key aspects include host rock lithology, tectonic and weathering history. Table 1 summarises the geological features that influence the geotechnical character for the mine site.

Table 1. Geological features influencing the local geotechnical character.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cainozoic cover</td>
<td>Comprising unconsolidated sands, sandy-clay, clays, and sandy-gravels resulting in variety of geotechnical materials.</td>
</tr>
<tr>
<td>Weathering</td>
<td>Tertiary age lateritic weathering profile overprints the stratigraphy. Depth of weathering can persist to at least 30m and create geotechnical materials ranging from ironstone to mottled fissured clays.</td>
</tr>
<tr>
<td>Igneous history</td>
<td>Dolerite sill intrusion ranging from fresh rock to distinctly weathered clay altered material.</td>
</tr>
<tr>
<td>Lithology</td>
<td>Ranging from silty-lithic sandstone, quartz sandstone, siltstone, laminated mudstone, carbonaceous mudstone, and coal. Weak layers such as coal, or clay-rich tuff plies and fissile mudstone can form discrete bedding plane shears. Most rock types tend to slake with prolonged exposure on the waste dumps.</td>
</tr>
<tr>
<td>Rock strength</td>
<td>Ranging from low to moderate and occasionally high.</td>
</tr>
<tr>
<td>Strata dip</td>
<td>Bedding dips range from $5^\circ$ to $13^\circ$ with local steeper dips as drag folds associated with faulting.</td>
</tr>
<tr>
<td>Bedding</td>
<td>Bedding partings are typically spaced from 0.1m to 1m.</td>
</tr>
<tr>
<td>Jointing</td>
<td>Usually 2-4 dominant sets resulting in an orthogonal blocky rock mass. Planar joint surfaces 0.3 to 1.5m spacing terminating at bedding partings.</td>
</tr>
<tr>
<td>Faulting</td>
<td>Thrust and normal faulting are common and form distinct and persistent curviplanar surfaces. Low strength dickite-kaolin clay, or calcite, and crushed rock infill can occur along the fault surface.</td>
</tr>
<tr>
<td>Water</td>
<td>Surface water seepage into the pits or waste dumps is a common cause for instability. Groundwater occurs as low flow rate seepage along discontinuities. The coal seams and faults act as the major aquifers.</td>
</tr>
</tbody>
</table>

Compressional tectonics has resulted in the development of large thrusts which ramp across the stratigraphy and sole along bedding. The thrusts are large and persistent curved structures and are often the cause for highwall instability. In combination, the dynamic nature of strip mining and the aforementioned geological features have potential to develop a variety of wedge or planar type failure mechanisms resulting pit and dump slope instability, requiring immediate geotechnical response and management.

3 The highwall failure events requiring a change in mine design

The pit orientation strikes north-south and is approximately 2.3km in length and the two coal seams dip around $5^\circ$ to $13^\circ$ to the east. Each strip is 80 meters wide at the base. The northern half of Strip12 is mined using cast blasting and truck-excavator methods. The southern half is referred to as the terrace mining blocks comprising development along strike and is operated using truck-excavator methods. The local topography is flat around 335RL and the highwall slope design comprises a $60^\circ$ batter from surface to 305RL, a 16m wide catch bench, then a single 50-60m high $70^\circ$ pre-split batter to the roof of coal. The 16m wide bench allows sufficient tail room for the large blast hole rigs to drill angled pre-split holes. The resulting overall slope angle for cast blasting the Strip 12 highwall is $57^\circ$. 
In November 2007 whilst mining coal from the northern end of Strip 12, the Mining Supervisor became aware of rocks dribbling from the highwall and ceased operations to investigate. All equipment and personnel were withdrawn from the immediate area and the highwall was visually monitored. Within 3 hours rock falls from the face increased, large cracks developed on the highwall face 50m north and south of the rock falls, and then a major highwall failure occurred where the early rock falls had been previously reported (Figure 1). The subsequent geotechnical investigation identified the probable cause of the failure to be related to coal mining activities removing toe support for the highwall, resulting in the movement along a large pit-ward dipping wedge-type failure mechanism controlled by two thrust faults. The strike of the main thrust fault was sub-parallel to the highwall, dipping 50° into the pit. The second thrust was striking almost perpendicular to the highwall and dipping at 50° to the north creating a wedge block around 140m long x 75m high x 60m wide. Further mining work in the failure area was suspended pending the completion of the geotechnical investigation and a decision to commence the next Strip 13. Mining operations were relocated to the south to continue overburden removal in the terrace block mining area. In addition a second 16m wide catch bench at the 275RL was included into the terrace block area mine design to provide additional rock fall protection and flatten the overall slope angle to 52° (Kelso and Bradfield, 2009).

![Figure 1. Strip 12 first highwall failure occurring November 2007 (140m long by 75m high and 60m wide).](image)

In March 2008, while stripping weathered overburden in the terrace mining block area, the new highwall started to develop wedge and planar type failures on a similar curved 60-50° pit-ward dipping fault surface (Figure 2). Dominant southeast striking joints dipping 80° to the southwest formed a progressive fretting wedge-type failure along the new highwall. At this time the highwall was 20m high and geotechnical advice recommended scaling the highwall back to the fault surface to remove the remaining weathered rock. This work was successfully completed by April 2008 and overburden stripping in the terrace mining blocks continued.
Second highwall instability March 2008 shows the highwall and pit-ward dipping thrust. The highwall behind the haul trucks was scaled back to the thrust surface removing the hangingwall block.

Following a production blast in June 2008, a large crack on the natural surface behind the crest of the terrace block highwall was reported. Upon inspection, the crack was located up to 80m east of the highwall crest. The cracking extended 700m south, from the November 2007 failure parallel to the highwall and linked into the March 2008 thrust fault exposed on the highwall (Figure 3).

Detailed geotechnical investigation ensued following the identification of the major crack and the steady movement around 2.5mm per day of the large highwall block toward the active pit void. This involved establishing daily extensometer monitoring, mapping the exposed highwall and surveying the position of other...
faults, and computer modelling these structures to create a 3D fault model. The pit was then divided into geotechnical domains based on identified structure and potential risk for further highwall instability. This was used in conjunction with geotechnical monitoring systems comprising extensometers and radar scanning for risk management purposes to allow overburden stripping and coal mining to continue in the terrace block area.

The second phase of the project involved the development of a geotechnical model to simulate the observed highwall movement. Two-dimensional limit equilibrium models were developed to simulate the failure mechanism, calibrate the effective shear strength properties for the thrust fault surface. Then possible mine redesign options were assessed, resulting in a 40m wide buttress at the highwall toe to stop the highwall block movement and safely complete mining the Strip 12 terrace block area which contained six months coal supply.

The maximum recorded total deformation of the highwall block from June 2008 to early January 2009 was estimated at 500mm, while deformation of the northern and southern ends of the crack ranged from 100-200mm. Over the 7 month monitoring period, this equated to an average daily deformation of around 2mm, and velocity approximately 0.1 mm/hour for the 700m-long highwall block.

Both the extensometers and radar scanning recorded steady daily velocities of approximately 0.1 to 0.3mm/hour (all velocities were based on a 12-hour period) from mid June 2008 to mid July 2008, as the overburden was stripped adjacent to the cracking. From mid July 2008 through to mid September 2008, the coal was exposed and attempts were made to mine this coal using the radar monitoring the highwall. Daily velocity then increased from approximately 0.25mm/hour to 0.5mm/hour, with peak values of 1mm/hour recorded by the radar and extensometers. The velocity measured by the radar in 1 hour intervals during this period was up to 2mm/hour. By mid September 2008 the 40m wide buttress was in place, and from this period the velocity declined to around 0.1 – 0.2 mm/hour. From mid October 2008 the highwall block had essentially stopped moving (i.e. velocity = 0.1mm/hour or less), and coal mining had progressed south past the cracked zone (Kelso and Bradfield, 2009).

## 4 Water and pit slope instability

Rainfall in the order of 5-25mm occurred several days prior to each of the instability events and it is likely that rainfall directly contributed to the initiation of the instabilities. The geotechnical monitoring data also recorded short-term increases in the rate of highwall deformation following isolated periods of rainfall. The impact from the rainfall was water ingress into the tension cracks, potentially softening of clay infill and reduction of the effective shear strength due to groundwater pressure increase.

Drainage assumed a key role for geotechnical management, and to reduce the potential impact from further rainfall, efforts were made to seal the cracks with clay and undertake surface earthworks to re-direct future runoff away from cracks and the failure areas. These efforts to manage surface water runoff, although difficult to measure the direct impact, were considered to be positive geotechnical measures to assist managing the then-current issues and prevent further instability developing.

## 5 The Highwall design

The typical Bowen Basin highwall design (the hardwall) comprises a bench at the base of the Tertiary horizon and also the base of weathering, and then a pre-split 65°-70° batter through fresh rock to the roof of the target coal seam. Based on the coal seam spacing there may be another bench on the coal seam floor then a further steep batter to the next seam. The Strip 12 hardwall slope design comprised a 16m wide bench at the base of weathering 25m below natural surface level, and then single pre-split batter around 60m high to 2m above the coal seam roof (Figure 4).
To achieve the steep highwall design, well controlled pre-split blasting is required and the batter is progressively scaled on each 4m flitch by the excavator to remove loose material from the final batter to expose the pre-split barrels. During wall scaling and coal mining along the toe, the large production excavator is positioned perpendicular to the highwall. When operating at full reach (around 15m), the excavator can scale the batter or pull-back the coal and load trucks whilst remaining outside the rock fall drop zone (typically 5-10m from the toe of the batter).

The steep hardwall slope design has been a safe and economic highwall design, but as the slope height progressively increases so too does the likelihood of exposing large and persistent faults or joints resulting in the development of failure mechanisms.

Options were investigated in late 2008 for an alternate highwall design that can adequately manage potential instability. A geotechnical study comprising mapping, kinematic and 2D limit equilibrium analysis during late 2008 were completed to assess future highwall design options to undertake mining the next Strip 13. The conclusion of this work indicated the highwall overall slope angle required reducing from 52° to 45° to further decrease the risk of thrust faults daylighting on a 70° batter (Figure 5).

The highwall design considered appropriate to account for known discontinuity orientations would comprise a 20m benched profile similar to conventional metalliferous open pits (Figure 6).
Figure 5. Stereonet summarising the mapped discontinuity data with respect to batter and overall slope angles (FA = fault, JN = joint, SH = shear).

Figure 6. The proposed Hardwall Strip 13 highwall design comprising a 20m benched 120m high slope profile.
6 The Softwall design concept and slope stability

The softwall design concept comprises an excavated $45^\circ$ slope cut through blasted rock with the purpose to fragment, rotate and disrupt persistent discontinuities within the rock mass and thus increase the effective friction angle along potential sliding or failure surfaces. Typical friction angles for faults with persistent planar to curved surfaces with polished or calcite infill can be in the order of $15^\circ$ to $20^\circ$. Thus a large fault striking at an acute angle to the highwall and daylighting on the pre-split batter poses a threat of planar or wedge failure. A blasted zone of rock in the highwall can disrupt the sliding surface and increase the effective friction angle to perhaps around $30^\circ$. The softwall will also permit local depressurisation and draining groundwater from the immediate pit slope, further enhancing the effective blasted rock mass friction angle.

It is critical the blasting design for the softwall accounts for the requirement to fragment and disrupt structure in the rock mass, but not the extent required for production blasting and efficient excavation. Blasting design resulting in high level of fragmentation could create a new hazard where the softwall mobilises in a circular rock mass failure mechanism.

The geotechnical studies undertaken in 2008 assessed options for the softwall design included a blasted 20m high stepped, or inclined blasted strip profiles (Figures 7 and 8).

---

**Figure 7.** Softwall 120m high slope with 20m high blasted steps.
The identification of further thrusts likely to be encountered in the next strip was not possible due to the lack of available data or time to undertake diamond core drilling. The ability to identify these structures in core or by geophysical methods is also problematical. Further limit equilibrium or numerical slope stability analysis would therefore be based on the location of inferred structures and risk becoming a misleading exercise. Thus based on previous slope history, geological mapping and collection of discontinuity data kinematic analysis became the determining feature for justifying ongoing highwall stability issues and the need for a mine design change to the softwall to manage the hazard (Figure 5).

Slope stability models for the hardwall and softwall design options were analysed by 2D limit equilibrium using the Sarma and Bishop methods to calculate the factor of safety (Table 2).

### Table 2. Slope stability model results.

<table>
<thead>
<tr>
<th>Slope stability model</th>
<th>Average factor of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardwall – 2 catch benches (OSA = 52°)</td>
<td>1.06</td>
</tr>
<tr>
<td>Hardwall – with buttress at the toe (OSA = 45°)</td>
<td>1.35</td>
</tr>
<tr>
<td>Softwall – blasted inclined strip (OSA = 45°)</td>
<td>1.68</td>
</tr>
<tr>
<td>Softwall – blasted 20m steps (OSA = 45°)</td>
<td>1.84</td>
</tr>
</tbody>
</table>

### 7 The economic aspects of the design options

Slope design requires optimising safety, operational and economic considerations. The 120m high softwall slope design was assessed from a mining cost aspect to determine the economic benefit compared with excavating a similar stepped hardwall design (Johnson, 2010).
Part of the economic analysis comprised comparing the drill and blast and excavation volume variances between the proposed highwall design options for the 2.3km pit length. The economic study used estimates for drill and blast costs for the standard steep pre-split highwall (the base case), non pre-split stepped hardwall, and two softwall options. The excavation cost was compared by volume differences compared to the base case design. The toe of the highwall was fixed to prevent loss of coal reserve.

Table 3. Volume increase compared with the 52° highwall.

<table>
<thead>
<tr>
<th>Slope Design</th>
<th>(m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwall 45°</td>
<td>961,770</td>
</tr>
<tr>
<td>Hardwall 45°</td>
<td>1,447,088</td>
</tr>
</tbody>
</table>

Table 3 indicates that although there is an overall mining cost increase laying the highwall from 52° back to 45° there will be a cost saving with reduced blasting and excavation cost to develop the softwall compared to the excavated 20m benched hardwall profile (Johnson, 2010).

8 Softwall slope performance

The project commenced in 2009 and is nearing completion with the softwall slope stability performance proving to be a successful design without incurring further slope instability during mining (Figure 9).

Figure 9. Looking across the pit to the softwall slope and in-pit waste dump developing behind the advancing terrace blocks.

The initial softwall blasts resulted in either too much or too little fragmentation to achieve the desired effect to disrupt rock mass defects and this resulted in difficulties in achieving the 45° slope profile. There has been progressive development of the drill and blast design parameters to improve both the fragmentation in the softwall, achieve the stepped design and reduce the blasting costs without compromising the slope stability.
production blasts designed for high fragmentation were modified in the back rows to achieve the disrupted softwall requirement.

Excavating the 45° batter through coal measures with large backhoe excavators created another issue. GPS guidance was installed on the excavator for the operator to pull the final slope to the design profile. Thick sandstone beds with orthogonal joints proved difficult to batter resulting in a stepped profile. This created a new potential geotechnical hazard where large blocks of sandstone toppled onto the slope and could potentially roll down the slope into the work area. This was managed on every flitch by operating the excavator at full reach while trimming the softwall batter and then constructing a 3m high safety bund offset 5m from the softwall slope toe to contain material rilling off the slope (Figure 10).

Figure 10. Looking along the strike of the softwall slope. Note the sandstone blocks resting on the slope as potential rolling rock hazard managed by chaining the crest and constructing a safety catch bund at the toe.

Minor slumping or settling of the slope in the order of 1m is occurring as evident by overlaying the end of month survey laser scans. However, no tension cracks have been identified along the crest or across the softwall slope indicating the development of rock mass or wedge type failure mechanisms.

The final pit floor was back filled immediately after coal mining to provide support to the toe of the softwall slope. Waste rock was hauled horizontally along strike to construct the in-pit dump in 3 lifts to back fill against the softwall and reduce the exposed extent of the slope and the potential for instability (Figures 9 and 10).

9 Conclusions

A robust highwall design is required for a large-scale bulk coal mining operation to minimise geotechnical hazards and resulting mining delays. The potential for further thrusts and wedge blocks that could be encountered and the associated risk for large-scale highwall failure required a mine design change to eliminate the hazard. The softwall highwall design presented a practical and economic solution to manage this hazard.
The softwall design has both advantages and disadvantages. The softwall has the advantage to permit continue mining the final Strip 13 with reduced risk of encountering a new thrust and developing further highwall instability. The softwall represented reduced direct mining costs for the 45° overall slope angle compared to the excavated hardwall. The softwall disadvantages for example include the inability to cast blast overburden in future strips resulting in possible higher excavation and haulage costs, and the softwall does not provide the opportunity to expose a clean batter for geotechnical mapping and hence the losing the opportunity to collect new data and reassess geotechnical conditions.

If a new mine design change is not properly implemented then a new set of geotechnical hazards can be created. In the softwall case this could be large-scale slumping or large rocks rolling down the slope and landing on the pit floor and active work areas. All geotechnical designs require a risk assessment before implementation and then a corresponding review and modification to operating procedures to manage new hazards. The advantage in the softwall case study is the reduction in the potential for large-scale highwall wedge failure and risk to people. The softwall highwall slope design has achieved this objective to reduce the risk to coal mining by managing a known potential geotechnical hazard.

10 Acknowledgments

I acknowledge Thiess Pty Ltd Australian Mining for the opportunity to publish this work. Leonie Bradfield and John Simmons provided their expertise and valued feedback while dealing with this challenging geotechnical issue. Sophia Johnson undertook the mining economics study as her final year honours thesis project.

11 References