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Elimination of structure controlled highwall failures at an open cut coal mine

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Abstract

Open cut coal mines, particularly fresh rock masses of open cut coal mines, experience few large highwall failures unless one or more unfavourable geological structures daylight. A number of challenges exist for identifying, analysis and operationally controlling the failure risk. The first challenge is to obtain accurate fault models (or planes) from traditional exploration by drill holes, until the geological structures are exposed on a highwall face and a coal seam roof. The second challenge is to acquire rock mass strengths and then to use process to assess the stability of the potential structure controlled failure. The third is to propose a most effective strategy to eliminate or control the potential large structure during pit design to coal uncovering stages, as soon as the fault structure plane becomes available. Consequently, the coal along the risk-eliminated area can be mined the safely to design. This paper presents details of confronting these challenges and examples of proactively managing highwall failure risks at a Bowen Basin open cut coal mine in Queensland, Australia.

Keywords: *open cut coal mine, geological structure, highwall, failure elimination*

1 Introduction

Open cut coal mining advances strip by strip of around 60–120 m width depending on machinery and geological conditions. The in situ rock mass slope located in the pit advancing direction is called highwall, while spoils placed above the previous strip pit floor is called lowwall. Depending on excavation equipment and vertical distances between adjacent coal seams, the height of highwall batters ranges from 15 to 60 m in general. The highwall above the bottom coal seam is normally the highest, if the coal seams are uncovered by a dragline.

Rock mass strengths of Bowen Basin coal measures were established in 1997 and formally published by Simmons (2018). It was found that these rock mass strength values are realistic, if not conservative, after having been applied at Bowen Basin coal mines since they were established. All slopes are stable if no adverse geological structures daylight and they all have a minimum design Factor of Safety (FS) of 1.2 (Wesseloo & Read 2009). Further rock mass strength review using empirical methods (Hoek 1998, 2007; Kalamaras & Bieniawski 1995) found that these strength parameters are conservative (Li et al. 2016), particularly for fresh Permian rock masses.

Failures of bench, inter-ramp and overall highwall in fresh Permian rock masses, regardless small or large, are almost all related to geological structures of joints and faults. Where a large geological structure daylight the conventional two-dimensional limit equilibrium slope stability analysis methods, such as Bishop, GLE/Morgenstern–Price, Spencer and Sarma methods, become inapplicable. Instead the wedge analysis could be applied. However, the results from wedge analysis may be misleading where the second structure forming the wedge does not exist in the highwall.

This paper reviews rock mass strengths using the empirical methods, then presents a highwall wedge failure and remediation process, as well as risk controls placed for eliminating future recurrences during design stages.

2 Highwall rock mass strength estimation

A dragline highwall is normally the highest single continuous batter in open cut coal mines. It is around 50–70 m vertically, including the bottom coal seam. Because of the height, any failure of the wall would potentially introduce a significantly high risk to personnel and equipment. Therefore, at the case study site presplit blasts are implemented for dragline highwalls at an angle of 65–70°. Figure 1 represents the rock mass conditions of the most dragline highwalls of the mine. Sandstone is the main rock mass of the highwall with few joints. The presence of small cling-ons or overhangs between presplit holes suggests high uniaxial compressive strength (UCS) value of the rocks. The highwall experienced no instability during both D4X and D05 seam mining.

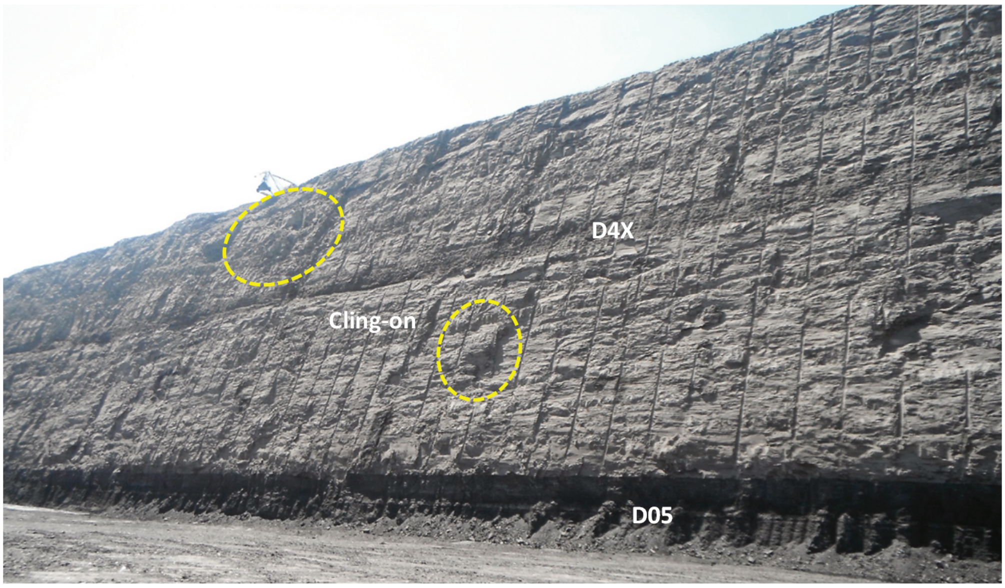


Figure 1 Rock mass conditions of most dragline highwall having few joints

For this mine in the Bowen Basin, the Permian rock masses are composed of sandstones in majority, siltstone and carbonaceous siltstones, as well as limited claystone. Laboratory UCS testing data for this case study site were reviewed, of which only the strength values of samples failed through intact rock at peak stress are considered (Li 2004; Villaescusa & Li 2004; Li et al. 2016). The testing data suggests that the fresh Permian intact rocks of sandstones, siltstones, carbonaceous siltstones and claystone have UCS values ranging from 7–70 MPa (Figure 2), and the fresh fine-grained siltstone and carbonaceous siltstone could have reasonably high compressive strength values. Note that the sandstones are the mainly rock mass composing the highwall of this case study pit. The strength distribution shown in Figure 2 also suggests that 86% of UCS values are 10 MPa or higher, and 76% of strength values are higher than 15 MPa. The fresh Permian intact rocks have an average UCS of 24 MPa and a standard deviation of 16 MPa.

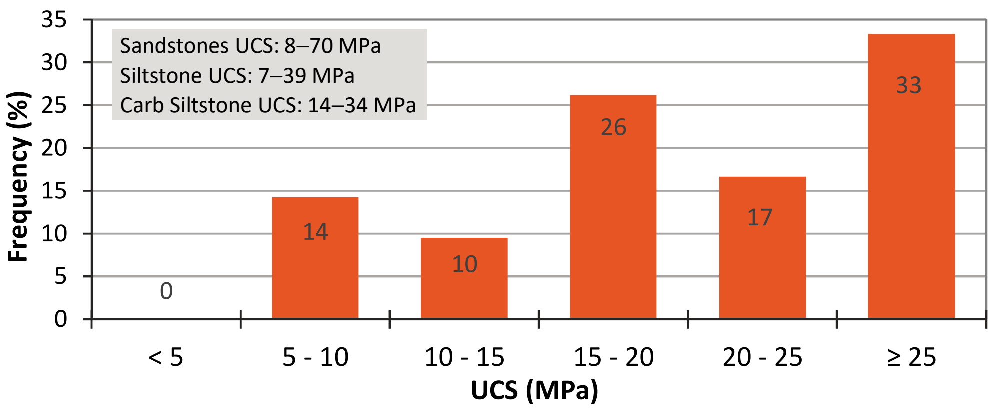


Figure 2 Summary of intact rock uniaxial compressive strength testing results of fresh Permian rocks

Rock mass quality is reviewed using the geological strength index (GSI). Table 1 presents the GSI estimations for general competent highwalls and jointed highwall rock masses. Note that jointed rock mass has rarely been observed in all pits of the mine in discussion. The GSI value for the general highwall looks realistic in relation to UCS data and actual rock mass conditions shown in Figures 1 and 2. The low GSI for the jointed rock mass is used for estimating the lower limit of the rock mass shear strengths.

In general, a dragline highwall is presplit, drilled and blasted for both ground control and draglines' optimal digging productivity. The presplit blast is normally fired before production holes are drilled to limit highwall damage from production blasting. A disturbance factor of D = 1 is, nevertheless, realistically chosen for the rock mass shear strength estimations.

Table 1 Details of geological strength index values for highwall rock masses

GSI = 74 for general highwall	GSI = 62 for jointed highwall (rarely observed)
2 for UCS = 5–25 MPa	2 for UCS = 5–25 MPa
17 for RQD = 75–90	13 for RQD = 50–75
15 for 0.6–2 m spacing	10 for 0.2–0.6 m spacing
25 for joint conditions	22 for joint conditions
15 for groundwater	15 for groundwater

The Hoek–Brown method of fitting Hoek–Brown criterion with Mohr–Coulomb criterion, in conjunction with Rocscience® RocData 5.0 software (Rocscience Inc 2019a), are applied to estimate the rock mass shear strengths. The 17 and 7 mi values are applied to sandstones and siltstones, respectively, which come from the table given in the RocData 5.0 software. The mi = 17 for the sandstone highwall rock mass shown in Figure 1 should be applied realistically to estimating rock mass shear strength. However, a mi = 12, average for sandstone and siltstones, is used.

Additional input parameters to those discussed above and shown in Table 2 are rock mass unit weight of 0.024 MN/m^3 and slope height of 60 m. The GSI values given in Table 1 are also reduced to the nearest five or 10 figures for rock mass shear strength estimation, as a conservative purpose.

Table 2 Rock mass strengths estimation using Hoek–Brown method and Rocscience® RocData 5.0 (Rocscience Inc 2019a)

Intact rock uniaxial compressive strength (MPa)	Geological strength index	Cohesion (MPa)	Friction angle (°)	Tensile strength (MPa)
10	60	0.21	30	0.02
15	60	0.25	33	0.03
20	70	0.43	41	0.10
24	70	0.48	42	0.11

In order to determine the lower limit of the rock mass shear strengths, the intact rock strength values of 10 MPa and 15 MPa are applied to the low GSI jointed rock masses. This is conservative when referring to the intact rock UCS distribution shown in Figure 2. Table 2 shows that the jointed rock mass have a cohesion (c) of 0.21 MPa and a friction angle (Ø) of 30°.

On the other hand, fresh Permian intact rock UCS values of 20 MPa and 24 MPa (the mean value) are applied to the high GSI highwall rock mass. The shear strengths for the most common fresh Permian rock masses are similar to those values have been applied to Bowen Basin coal mines in Queensland, Australia for at least 20 years (Simmons 2018), which are $c = 0.45$ MPa and $\emptyset = 42°$. The estimated rock mass shear strengths given in Table 2 confirm that the shear strengths of fresh Permian rock masses from Simmons (2018) are realistic in this case study.

Table 2 also gives tensile strength of rock mass, which are very low particularly for more jointed rock masses. These low tensile strength suggest that the rock mass is easily subject to tensile failure as soon as the rock mass experiences any tensile stress.

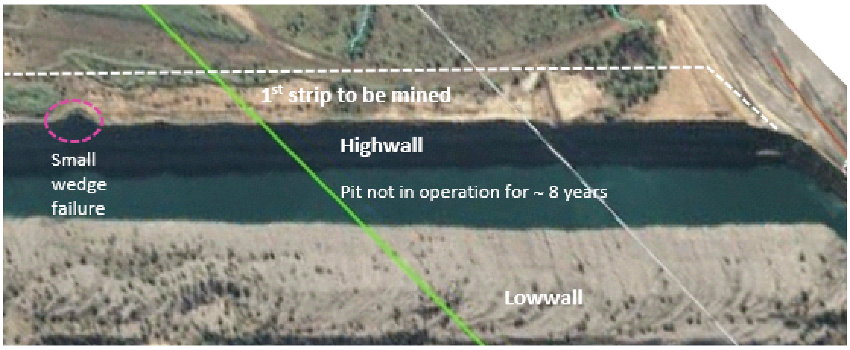
3 Highwall failure and related ground control measures

3.1 Pit and highwall failure history

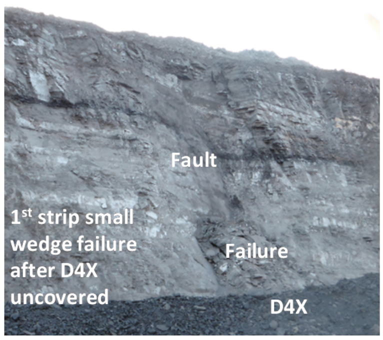
The study site for this paper is an open cut coal mine that started operations in 2014. The pit was taken over from a neighbouring mine and had been a water storage for around eight years. Due to the change of ownership and personnel turnover, minimal information was available regarding the historical pit performance, except a small wedge failure observed from pit highwall (Figure 3a). The pit was subsequently dewatered and mud removed, and experienced no highwall instability at this time.

Mining activities in this pit recommenced in early 2016. Two coal seams, D4X and D05, were to be uncovered by a dragline. The upper D4X seam was 18 m below the highwall crest, while the bottom D05 seam (with a thickness of 6 m) was 46 m below the highwall crest vertically. The highwall was designed at 70°, and presplit holes were drilled and blasted from the crest down to the D05 seam roof.

A small fault controlled planar failure was observed after the D4X seam was uncovered (Figure 3b). Visual monitoring was implemented by open cut examiners and geotechnical engineers, the safety and operational risk was managed by keeping a 10 m standoff from highwall. The D4X coal was mined to design and the D05 overburden was drilled and blasted as planned.



(a)



(b)

Figure 3 (a) Pit status prior to the first strip mining after abandoned for around 10 years; and (b) A small highwall instability above D4X

Significant highwall slumping and subsidence along the same fault occurred during D05 overburden blasting (Figure 4). The photo was taken from the low wall around 300 m away from the highwall, as access on the crest bench had been blocked by the mud waste material from the pit cleanout in previous strip. Observations of the face and crest bench later (Figure 5) found that:

1. Few cracks presented on the highwall face.
2. The closer to the highwall and fault intersection, the greater the subsidence and movement of the highwall.
3. No adverse structure was present at the southern end of the subsidence to form general wedge failure.
4. Open cracks #4 to #6 shown in Figure 5a, at the southern end of subsidence, intersected crest at an angle from 60 to 70°.

The subsidence and open cracks suggested that the whole rock mass was acting as a cantilever with the southern limit as the end point. The open cracks developed due to the tensile stress exceeding the rock mass tensile strength (Table 2).

The unstable area was approximately 100 m in length along highwall crest and up to 25 m wide behind the highwall crest, with a total unstable volume of around 5,000 m^3. The safety and operational risks would be very high if the failure were not managed and controlled.

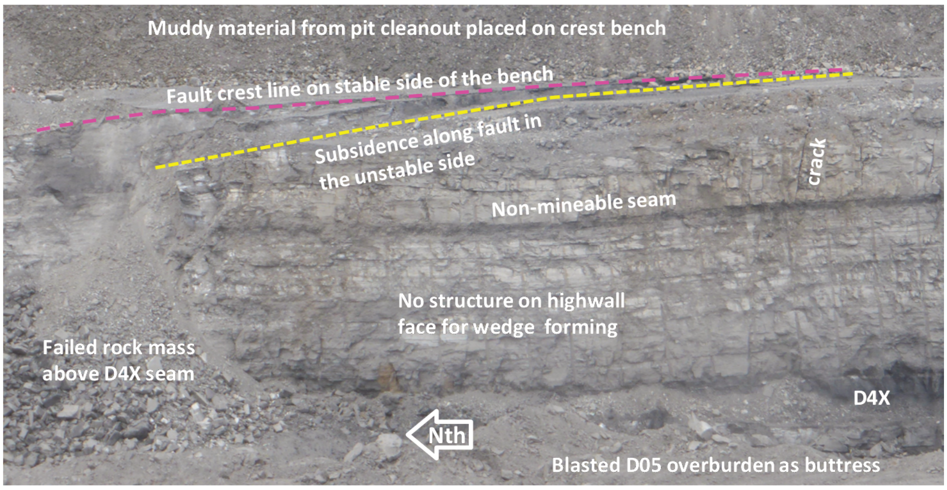
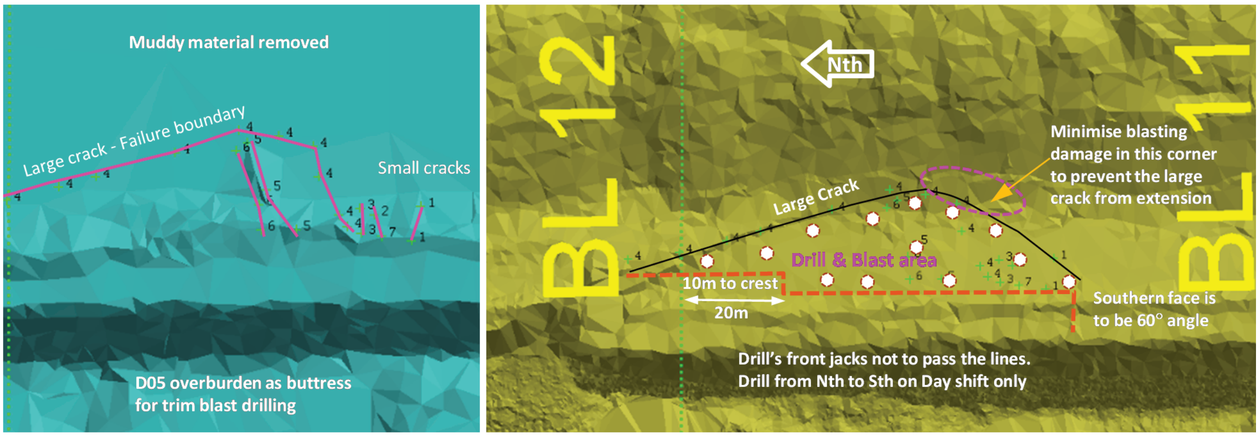


Figure 4 Highwall slumping and subsidence along the fault caused by D05 overburden firing

The risks were that the rock blocks were too big to be handled by dragline and unsafe and time-consuming for a dragline to scale the area to stable. Geotechnical recommendations were to blast the unstable ground first (called trim blasting), and followed by dragline removal and scaling. As the blasted D05 overburden acted as a buttress and stopped the unstable ground further moving, drilling within the concerned area proceeded with an 8 to 10 m standoff from crest, and drilling on day shift only (Figure 5b). A 3 m high bund around 150 m long was installed on the bench below, on top of the blasted D05 overburden, at a minimum 20 m from D4X highwall toe.



(a) (b)

Figure 5 Cracks at (a) Southern end of the failure; and (b) Trim blast drilling controls

This highwall risk was successfully managed by the trim blasting and dragline scaling. Figure 6 shows a stable 46 m high batter after the remediation processes was completed. In addition, the rock mass looked more competent than that shown in Figure 4, when the highwall face had been contaminated by dust. Financial losses incurred by this failure were some schedule delays and loss of approximately 1,000 t of D4X coal within the failure area.

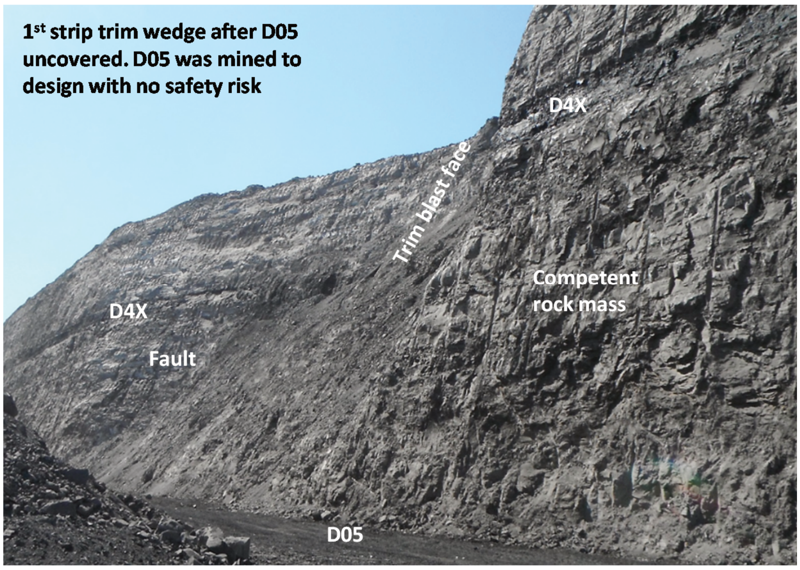


Figure 6 Highwall failure risk eliminated after trim shot blasting and dragline scaling

3.2 Geotechnical design review and assessment for further mining along the fault

In reviewing exploration data and fault exposures on the crest bench of this pit, it was found that this fault would impact on highwall stability of the next eight strips. The conventional strategy for dealing with this kind of situation was to implement a softwall, i.e. blasted highwall rock mass with a 45° batter from the bottom seam roof to highwall crest (Figure 7). This strategy introduces not only more blast damage to the fault and highwall corners, but also more quantity of material to fit into the limited space of lowwall. Otherwise, some of the overburden material would have to be removed by more costly truck and shovel fleets. An advantage of the softwall strategy is that the accuracy of the fault model or its orientation are not critical, as the fault is always disrupted by blasting within the softwall.

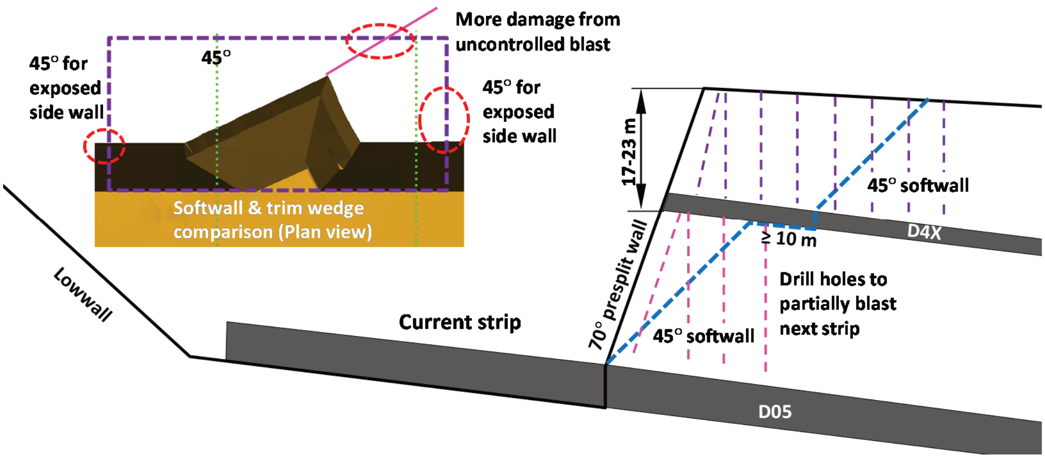


Figure 7 Sketch for softwall strategy and a comparison with trim wedge blast strategy

Due to the success of the first strip risk control, the trim wedge blast strategy is proposed to all future strips associated with this fault. It was known that the fault had an orientation of 60° in dip and 190° in dip direction from the first strip. Even though there was no adverse structure in the southern side to form a normal wedge failure, a surface at around 60° to highwall can be assumed based on the past observation and experiences. Therefore, a wedge analysis can be carried out using Rocscience® Swedge 6.0 software (Rocscience Inc 2019b). Figure 8 shows the input parameters and stability analysis results.

Shear strengths of the fault are conservatively assumed as $c = 0$ and $\emptyset = 10°$, even though the exposed fault footwall face was not smooth. Applying the low shear strength is to minimise the contribution of the fault on the FS value in the wedge stability analysis. On the other hand, the shear strengths of rock masses should be applied to the trim blast face, as no actual structure exists in the highwall. The FS values shown in Figure 8 are higher than the minimum FS of 1.2, even with the jointed rock mass strengths ($c = 0.21$ MPa and $\emptyset = 30°$). Therefore, the wedge or highwall near the fault should be stable if solely judged with the FS values and ignoring the actual tension failure mechanism. This outcome can suggest that the FS and strengths of structure and rock mass are not as critical as the accurate fault model in wedge stability analysis.

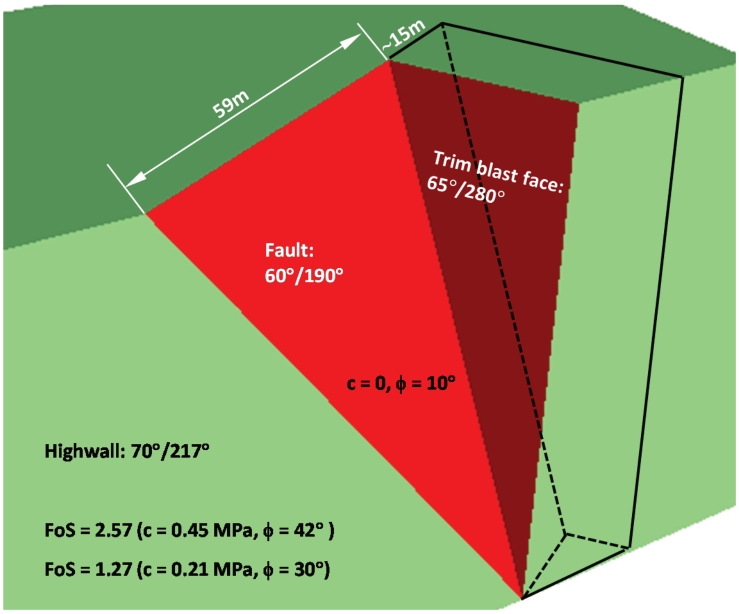


Figure 8 Wedge analysis results and proposed trim blast face orientation and location

However, the wedge dimensions from the wedge analysis are useful, particularly the side length along the fault (59 m in Figure 8) can be used to determine the trim blast face location. The Rocscience® Swedge 6.0 (Rocscience 2019b) software thus becomes a very good geometrical analysis tool for all similar situations. The actual trim blast face is designed approximately 15 m further along the fault, in order to account for orientation variation of the fault and blasting damage at the wedge toe. The coal within the trim wedge can either be mined together with current strip or reserved for the next strip.

Figure 9 shows the pit design incorporated with geotechnical controls for the fifth strip of the pit, the first time the D05 coal within the trim wedge was kept in place without being uncovered and mined. Operations are keen to mine as much coal as possible if uncovered. This may compromise safety sometimes. Therefore, leaving a spoil buttress and not uncovering the bottom coal seam within the trim wedge can operationally avoid confusion on digging limit.

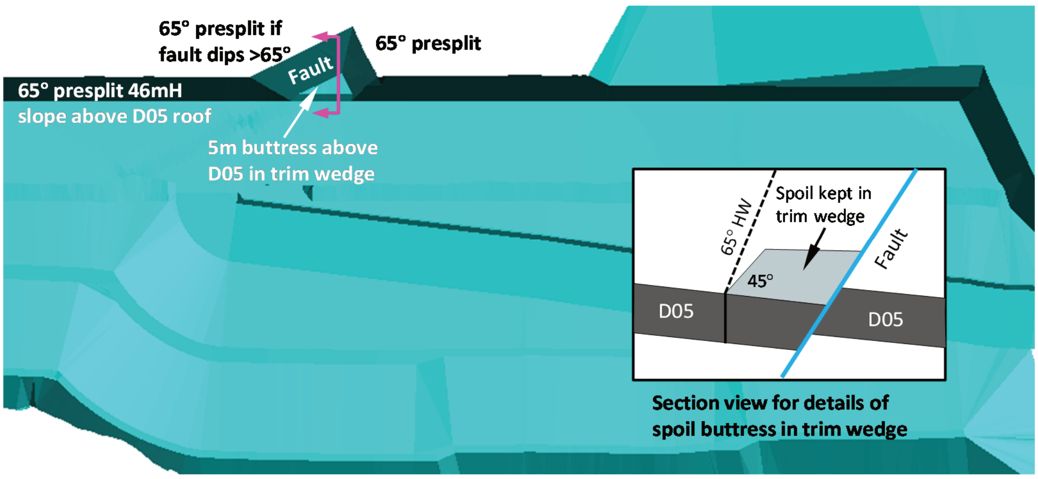


Figure 9 Plan view of pit design incorporated with geotechnical risk control for the fifth strip onwards

In addition, leaving the buttress can stop potential toppling failure happening if structures of having opposite orientation to the trim blast face present in the highwall. The highwall slope has been reduced to 65° from the fifth strip onwards, due to an adjacent pit experiencing a planar highwall failure along structures oriented at around 70° dip.

Since the first strip highwall failure, four more strips have been fully mined out. The sixth strip has completed the D4X mining and the D05 coal uncovering is in progress. No highwall failure was experienced after implementing the trim wedge blast strategy, i.e. the highwall failure risk was managed by the trim wedge blasting. Survey scans for the second to sixth strips shown in Figure 10 confirm the effectiveness of the strategy.

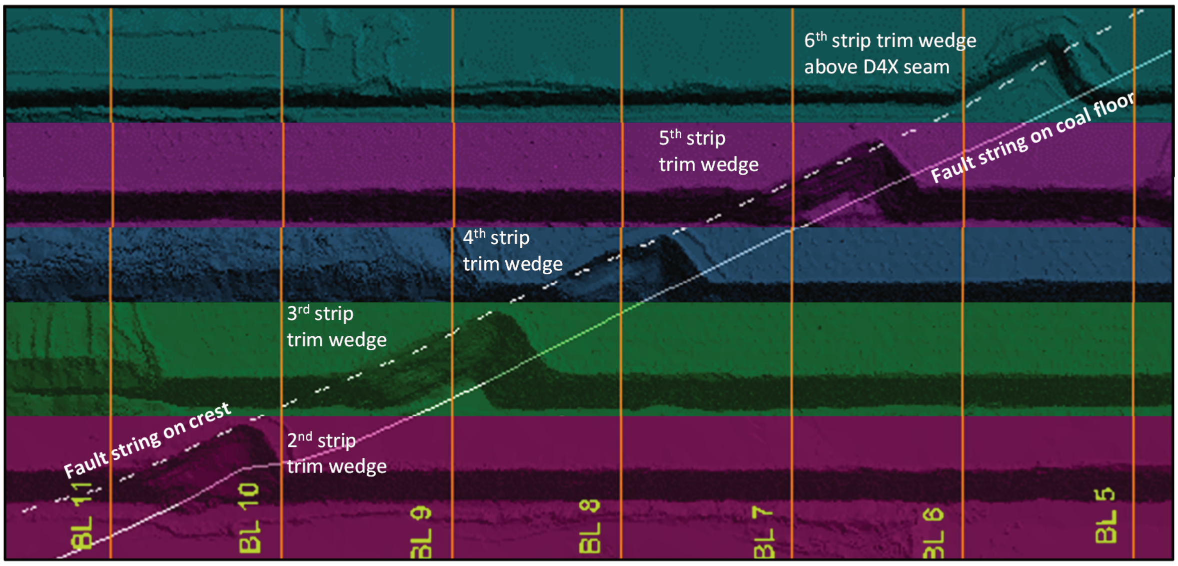


Figure 10 Survey scans for all mined and mining strips so far showing successful risk elimination outcomes

The fault line on the crest level was well-aligned with the actual fault exposure until the fifth strip. The fault in the sixth strip became steeper at around 70°. The batter along the fault was presplit blasted to 65° in order to improve slope stability. Figure 11 shows the outcome of the third strip as an example of the trim wedge blast performance and also displays rock mass conditions around the trim wedge.

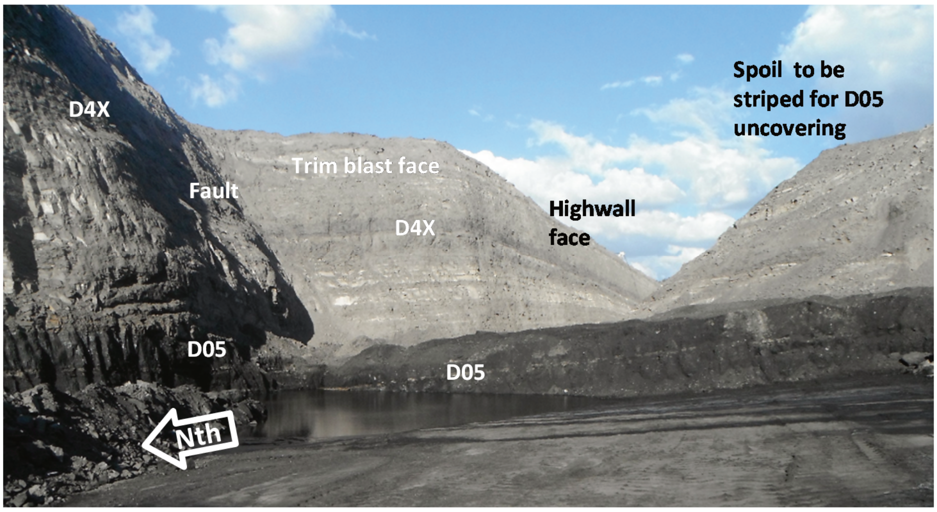


Figure 11 Photo of the trim blast wedge for the third strip

Over the years, similar but smaller potential and actual highwall failures were experienced in other pits of this mine. The same approach of wedge analysis was successfully applied to either actual failure remediation or potential highwall failure elimination design. Besides the safety achievement, the economic benefits from the risk controls are the minimised coal delay, mining coal under a failure to next strip, and avoiding associated re-uncovering costs.

4 Conclusion

Fresh Permian highwalls in the Bowen Basin open cut coal mines rarely experience failures unless adverse geological structures are present. Where an adverse fault structure exists, risk levels of a highwall failure depend on the slope height and orientation of the fault. The traditional softwall strategy can be applied to manage this risk. However, the trim wedge blast strategy presented in this paper is an alternative but simpler approach for risk management of highwall failure.

Work presented in this paper found that:

1. The shear strength of fresh Permian rock masses proposed by Simmons (2018) are applicable to general slope design assessment.
2. The strengths of structure and rock mass, as well as the resulted FS are not important if no wedge forming structures daylight in highwall.
3. Instead, the geometrical parameters of the wedge, particularly the structure orientation and location, are critical for determining the optimal location of the trim blast face or remediation boundary for the expected failure.
4. The trim blast face should intersect the highwall at an acute angle of around 60°.
5. The bottom coal seam within the trim blast wedge should be reserved for the next strip, where the buttress, as high as practical, would help stop potential toppling failure if toppling prone structures are present in the highwall.

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References

Hoek, E 1998, *Practical Rock Engineering*, viewed 2 October 2000, http://www.rocscience.com/roc/Hoek/Hoek.htm

Hoek, E 2007, *Practical Rock Engineering*, viewed 28 August 2019, https://www.rocscience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Full-Text.pdf

Kalamaras, GS & Bieniawski, ZT 1997, 'A rock mass strength concept for coal seams incorporating the effect of time', in T Fujii (ed.), *Proceedings of the 8th International Congress on Rock Mechanics,* A.A. Balkema, Rotterdam, vol. 1, pp. 295–302.

Li, J 2004, *Critical Strain of Intact Rock and Rock Masses,* PhD thesis, Curtin University of Technology, Perth.

Li, J, Tucker, N & Todd, JK 2016, 'Impact of rock mass strength parameters on lowwall stability assessment outcomes in open-cut coal mines', in A McConnell, R Kelly & B Lehane (eds), *Proceedings of the Fifth International Conference on Geotechnical & Geophysical Site Characterisation*, International Society for Soil Mechanics and Geotechnical Engineering, London.

Rocscience Inc 2019a, *RocData*, version 5.0, computer software, Rocscience Inc, Toronto, https://www.rocscience.com/software/rocdata

Rocscience Inc 2019b, *Swedge*, version 6.0, computer software, Rocscience Inc, Toronto, https://www.rocscience.com/software/swedge

Simmons, JV 2018, 'Weak coal measures', in Martin D & Stacey P (eds), Guidelines for Open Pit Slope Design in Weak Rocks, CSIRO Publishing, Australia, pp. 205–223.

Villaescusa, E & Li, J 2004, 'A review of empirical methods used to estimate rock mass compressive strength and deformability in mining industry', in A Karzulovic & MA Alfaro (eds), *Proceedings of MassMin 2004,* Instituto de Ingenieros de Chile, Santiago, pp. 59–68.

Wesseloo, J & Read, J 2009, 'Acceptance criteria', in J Read & P Stacey P (eds), *Guidelines for Open Pit Slope Design*, CSIRO Publishing, Clayton, pp. 221–236.