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A Review of Highwall Mining Experience and Practice

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A REVIEW OF HIGHWALL MINING EXPERIENCE AND PRACTICE

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Abstract: The highwall mining method originated in the USA in the 1940s. The aim of the method was to recover coal from a surface mine that has reached its economic limit. The coal is accessed at the base of the highwall from where a series of parallel entries are driven into the coal seam. Since 1991, highwall mining has been commercially used in Australia in approximately 40 pits at 17 coal mines (Christensen, 2004). Highwall mining provides opportunities to extract additional reserves with high productivity compared to underground operations and conventional surface operations. Therefore, some of open cut mines may consider adopting highwall mining as an alternative mining system when uneconomic conditions are expected due to higher stripping ratios. This paper reviews the highwall mining experience and design practices with an emphasis on geotechnical considerations. In addition, the relevant design issues for future research topics and challenges on highwall mining are discussed to enhance both the productivity and mine safety from the geotechnical point of view.

INTRODUCTION

Highwall mining refers to a mining method to recover coal from a surface mine that has reached its economic limit. The coal is accessed at the base of the highwall from where a series of parallel entries are driven into the coal seam. The entries are mined using two types of highwall mining systems, namely, continuous highwall mining (CHM) and auger mining (Figure 1). CHM system utilises a continuous miner generating typically 3.5 m wide rectangular entries while auger system excavates single or double holes typically from 1.5 to 1.8 m in diameter (Duncan Fama *et al*, 2001). The penetration depths range from 50 to 500 m (Verma *et al*, 2013) depending on the highwall mining systems and mining conditions. The pillars are then left between the mined entries to support the overburden.

Figure 1: Highwall mining systems (a) CHM system (after Caterpillar Inc.), (b) Auger mining system (Coal Augering Services 2014)

Highwall mining has several advantages compared to underground operations and conventional surface operations. Firstly, due to its flexibility and mobility, it is easier to recover smaller blocks of coal, which allows additional coal recovery from a final highwall or in constrained areas such as service corridors, spoil heaps and rivers (Shen 2014; Kleiterp 2010 and Fan, 2015). Secondly, highwall mining method is cost competitive as only three to seven crew members are needed (Luo 2013 and Schmidt 2015) and no roof bolting is required for the entries. Capital cost is less than underground mining with the average production capacity of in excess of 1 Mtpa (Shen 2014). Moreover, highwall mining is a safe mining

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method. Because the operators remain out of the entries they are not exposed to hazardous events such as roof and rib falls, mine fires and coal dust within the entries (Luo 2013).

Currently, the auger mining method can penetrate up to 200 m long and produce up to 60,000 tonnes of coal per month while the CHM method can drive up to 500 m and produce up to 124,000 tonnes per month (Shen 2014). Due to its longer penetration depth and productivity, CHM systems are preferred and more widely used than auger mining (Shen 2014 and Luo 2013). Even though a single CHM system rarely exceeded a production rate of 1.25 Mtpa in practical, its highest capacity of 1.5 Mtpa was proposed with upside of 2.0 Mtpa (Christensen 2004).

Therefore, some of open cut mines may consider adopting highwall mining as an alternative mining system when uneconomic conditions are expected due to higher stripping ratios or equipment availability. This paper reviews the highwall mining experience and design practices with an emphasis on geotechnical considerations. In addition, the relevant design issues for future research topics and challenges on highwall mining are discussed to enhance both the productivity and mine safety from the geotechnical point of view.

HIGHWALL MINING EXPERIENCE

History of highwall mining

The information below on the history of highwall mining is mainly based on the reviews from Kleiterp (2010), Gardner and Wu (2002), Zipf (2006), Marshall *et al.,* (1988), Duncan Fama *et al.,* (2001) and Schmidt (2015).

In the 1940s, highwall mining method originated in the USA to mine additional coal from outcrops in contour mining, as a type of auger system. The first auger system excavated a single hole of 1.5 m in diameter and 30 m long, and recovered 726 tonnes of coal per day with a four-man crew. While the auger mining system was regarded as a new productive mining method, some problems encountered with the increased penetration depth of up to 120 m. The operations had to cease when a coal seam became thinner than the diameter of the auger hole. If a coal seam was thicker than the diameter, a significant amount of coal within the seam was left behind, resulting in low recovery. Even with other concerns, such as intersection of adjacent holes due to poor alignment, production from the auger method peaked in the 1970s with a perception of an inexpensive mining method.

In the meantime early CHM concepts evolved and the current CHM systems emerged in the mid-1970s. In 1981, the RSV thin seam miner, also known as the Metec Miner or Dutch Miner, was introduced. The machine first adopted a drum cutterhead used in underground mining, enabling full excavation of coal seams that vary in thickness. Since the early 1980s, the CHM systems have commercially been used in the USA and the developments of new CHM systems continued, including Tramveyor, Archveyor, Addcar system and Superior Highwall Miner. In the 2000s, the Superior Highwall Miner and the Addcar system were two dominant manufacturers for highwall mining system. In 2014, Addcar was acquired by the Australian company, UGM Mining Solutions.

In the USA, the total run of mine production from highwall mining was estimated to be 59 million tonnes in 2003, consisting of approximately 45 million tonnes from CHM and 14 million tonnes from auger mining, which may account for 4% of total coal production in the country (Zipf and Bhatt 2004). Other countries such as South Africa, India, Russia, Colombia and New Zealand also use highwall mining (Schmidt 2015 and Porathur *et al.*, 2013).

Highwall mining in Australia

Duncan Fama *et al.,* (2001) summarised the introduction of highwall mining in Australia: In 1989, highwall mining method was first introduced into Australia. As a trial, ten rectangular entries were mined up to the penetration depth of 30 m at the Moura Mine. In 1991, Callide Mine commenced commercial highwall mining with auger system. German Creek and Oaky Creek Mines also applied auger mining after the operations in Callide mine. In 1993, Oaky Creek Mine commenced operations with CHM system.

Since 1991, the commercial highwall mining operations have been conducted in approximately 40 pits at 17 coal mines (Christensen 2004). The following coal mines are reported to use highwall mining method (Duncan Fama *et al*, 2001 and Christensen, 2004):

- CHM system: Oaky Creek, Moura, German Creek, Ulan, Collinsville, Yarrabee, Newlands, Charbon, South Blackwater.
- Auger system: Oaky Creek, Moura, German Creek, Callide, Warkworth, Liddell, Charbon, Gregory, South Blackwater, Goonyella, Jellinbah, Wambo, Foxleigh.

In terms of production figures, 20 Mt of coal have been produced from CHM method and 5 Mt of coal from auger method with peak production of between 3 and 4 Mtpa in 1997-98 (Christensen 2004). During the period of widespread application of highwall mining, the mining method proved to be a productive and safe technology (Christensen 2004) while the mining industry experienced at least 7 panel failures and 3 major roof collapses at different coal mines, which impeded mining operations and sometimes caused damage to the equipment (Shen and Duncan Fama 2001). It is estimated that due to increase in coal prices in the early and mid-2000s the use of highwall mining declined in Australia. It is however anticipated that with the recent lower coal prices some of the open cut mines will be uneconomical due to high stripping ratios and highwall mining will be considered again.

GEOTECHNICAL CONSIDERATIONS IN HIGHWALL MINING

Figure 2 shows a typical panel layout for highwall mining. Given that CHM system is the preferred method over auger mining in the industry, only the considerations for CHM systems are considered in this paper. The panel layout incorporates the web pillars, generated by excavation of a series of entries, and the barrier pillars that are left between the panels to ensure the panel stability. The typical geometry indicates that pillar design in highwall mining has a common ground with that in underground mining. Therefore most of the mechanics for underground pillar design also apply to highwall pillar design (Perry *et al.*, 2015). In this context, the key concepts for highwall pillar design involve panel widths, web and barrier pillar widths as well as the pillar width to mining height (w/h) ratio of pillars, which are somewhat similar to underground coal pillar design.

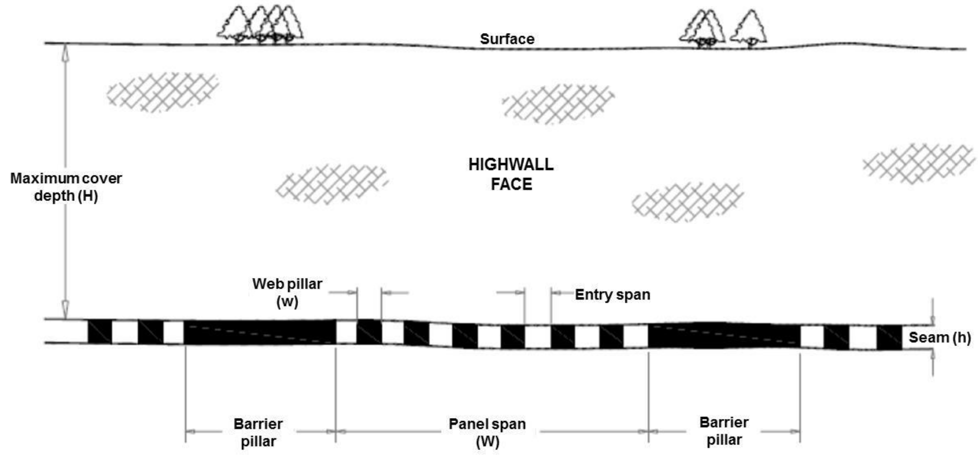

Figure 2: Typical panel layout for highwall mining (after NSW DPI technical reference CTR-001)

In some areas, however, highwall pillar design has its own distinct features. Due to the relatively shallow overburden depth compared to underground mining, the web pillars in highwall mining are typically slender (w/h<3) (Mark, 2006). This is demonstrated by a database of the failed Australian CHM pillar cases with the w/h ratios from 0.6 to 1.4 (Hill 2005). This slender type of pillars are known to fail suddenly accompanying catastrophic domino failures, on the contrary to the non-violent pillar squeeze for larger w/h ratio pillars (4<w/h<8) or the strain-hardening behavior for squat pillars (w/h>10) (Mark 2006). In addition, due to its long penetration up to 500 m, the pillars are not square, but rectangular. Thus, this specific geometry should be considered for pillar design in highwall mining.

Another distinct feature of highwall mining is that the mined entries are excavated by the remotely controlled miner and no roof support is installed. Hence, the entries should be fully mined as soon as possible to avoid time dependent deterioration of roof. For example, the 300 m entry is typically developed in 10-12 hours (Guo *et al.*, 2010). If roof falls occur in the highwall entries the mining operations can be hampered severely. The CHM system can tolerate minor roof falls less than 0.1-0.2 m thick while major roof falls greater than 0.3 m thick enable the equipment to be damaged or even buried (Shen and Duncan Fama 2001). In addition, the roof falls cause the adjacent web pillars to increase their pillar height. The heightened pillars in turn reduce the factor of safety (and the w/h ratio) resulting in the decrease in pillar stability (Shen and Duncan Fama 1999). In this respect, the roof competency has been recognised as one of the most important parameters in highwall mining in Australia (Duncan Fama *et al.*, 2001). It is therefore suggested that the roof span stability assessment should be carried out prior to the commencement of highwall mining operations.

The stability of highwall itself is also critical because the operators and mining equipment are located at the base of a highwall. In general, the highwall itself is stable as the highwall is generated with adequate design and good blasting practices (Fan 2015 and Zipf and Mark 2007). However, the highwall can be destabilised (prior to CHM mining) due to various factors including groundwater flow, weathering, vibration etc (Gardner and Wu 2002). Shen (2014) classified highwall instabilities into three categories based on scales as follows:

- Mass instability: deep seated movement of rock mass into the pit, caused by subsidence or major faulting.
- Face instability: failure at the highwall face due to incomplete pre-split blasting or joints parallel to the highwall face.
- Block instability: localised falls of rock blocks or wedges from the highwall face at various sizes.

Hence, highwall stability should be assessed prior to commencement of highwall mining operations, by means of highwall mapping to identify highwall instabilities (Shen 2014). Once any issues are identified, the preventive measures should be taken, such as guiding an appropriate distance from the highwall face, abandoning a hazardous area, re-blasting the wall and monitoring for wall movement (Shen 2014 and Gardner and Wu 2002). In addition, highwall stability should be assessed during and after the highwall mining operations. This is because of the fact that excavation at the bottom of the highwall may have an impact on the highwall stability. Thus, appropriate pillar design especially for the area of the entry is needed to reduce the likelihood of highwall instability (Fan 2015). An adequate design for entire pillar system is critical as the web pillar failure can lead to a catastrophic highwall failure (Zipf and Bhatt 2004).

Water flow into the mined entries enables mining conditions to deteriorate. Duncan Fama *et al.,* (2001) reported a few cases including a case where reduction in pillar strength led to a panel failure, another case where the weakened coal joints led to a roof failure and an incident of sinking miners into the soft floor. The excessive water flow was believed to contribute to all of those failures. Based on the survey on highwall mining performance in the USA, water problem was one of the most critical factors that impeded the full completion of entries as well as rock fall (Zipf and Mark 2005).

Methane content sometimes hinders highwall mining operations. The suggested maximum level for methane content within a seam is 10 m^3/tonne (Duncan Fama *et al.*, 2001). To prevent from the explosive gas, the Moura Mine used an automatic shutdown approach with the equipment when explosive concentrations were encountered, whilst inert gases such as carbon dioxide, nitrogen and boiler gas were tested to dilute the gas to a certain level (Mossad *et al.*, 2009).

DESIGN PRACTICE FOR HIGHWALL MINING

Panel/pillar stability

There have been significant advances in underground pillar design with empirical approach. With the database from both successful and unsuccessful case histories, empirical formulae have been derived and successfully employed in the mining industry. Of note is that no sufficient historical data was accumulated when CSIRO initiated highwall mining design guidelines for Australian conditions in the 1990s. The UNSW pillar design methodology was developed in 1995, encompassing squat and rectangular pillars. However, the methodology is not recommended to determine the pillar strength for highwall mining as the highwall pillar widths are outside the empirical data regime in the derivation of those strength formulate (Galvin 2010). Considering the factors such as rectangular pillars, pillars with weak or sheared end constraints, asymmetric loading due to dipping seams or varying overburden depth etc, numerical modelling was used to estimate the strength of pillars in highwall mining conditions described above (Duncan Fama *et al.*, 1995).

Numerical modelling was also used to determine the global layout design. The analysis was carried out to calculate overall "layout strength", which considers the stability of both individual pillars and the whole mining panel (Adhikary and Duncan Fama 2001). The layout strength is defined as the maximum stress level that the layout remains stable, which is determined by gradually increasing the stress until all pillars are yielded through. Then the safety factor, the ratio of the layout strength to the actual estimated cover stress at any given penetration depth, is determined (Duncan Fama *et al.*, 2001).

NSW DPI (2008) proposed the best practices on highwall mining design using the following empirical guidelines:

- When determining the strength of web pillars, this guideline uses the following values that were calculated in the research of Duncan Fama *et al.,* (1999):

Table 1: Estimates of web pillar strength

Situation	Web pillar strength (MPa)
Strong coal, strong contacts	6.0
Strong coal, weak contacts	5.1
Weak coal, strong contacts	3.6
Weak coal, weak contacts	3.1

- Pillar load is calculated by tributary area theory. The maximum overburden depth of the layout is taken to determine the load.
- Then, a minimum safety factor of 1.6 is suggested for new highwall mining operations where no guidance system is employed. When a reliable guidance system is employed, a minimum safety factor of 1.3 is suggested as best practice. A minimum web pillar w/h ratio of 1.0 is also suggested.
- To prevent catastrophic web pillar failures, the maximum critical panel width is restricted to the value that is equal to the shallowest depth of overburden. A minimum pillar w/h ratio of 4 is suggested for the barrier pillars.

In 2006, the U.S. National Institute for Occupational Safety and Health (NIOSH) has developed a pillar design tool for highwall mining, ARMPS-HWM (Analysis of Retreat Mining Pillar Stability - Highwall Mining) (Anon 2006). ARMPS-HWM used the Mark-Bieniawski formula, which was first developed for rectangular pillars in underground retreat mining (Mark and Chase 1997). The tributary area theory is used to estimate pillar stress with the maximum overburden depth or weighted average depth, which is defined as the sum of 0.75 × the maximum overburden depth and 0.25 × the minimum overburden depth. Subsequently, the program provides design guidelines with suggested safety factors.

While this empirical approach is widely employed and regarded as an acceptable methodology in the USA, the design resulted from ARMPS-HWM is often compared and verified with numerical modelling. The reason is that the empirical method doesn't usually take into account the site-specific information. Vandergrift *et al.,* (2004) described an example of using LAMODEL and UDEC to validate the preliminary design from the empirical tool and to carry out stability analysis of the roof and floor. Perry *et al.,* (2015) also presented an utilisation of FLAC3D, which indicated the possibility of over-designed pillars from ARMPS-HWM.

Entry span stability

Duncan Fama *et al.,* (2001) presented the analytical, numerical, and empirical tools that can be used to assess the entry span stability. CSIRO has developed two analytical models, the laminated span failure model (LSFM) and the coal roof failure model (CRFM), to assess the two dominant failure mechanisms, namely (i) span delamination and snap-through for rock roof and (ii) coal beam shear failure mechanisms in case of leaving coal in the roof (Figure 3). These two among other failure mechanisms are applied to the typical Australian mining conditions of laminated roof with low to moderate *in situ* stresses. The LSFM predicts the probability of roof falls and the average height of the falls whilst the CRFM calculates the safety factor of coal roof. Numerical approaches such as FLAC or UDEC are conducted when the span failure is expected to be caused by two or more different mechanisms, or the geology is complex to adopt the analytical methods.

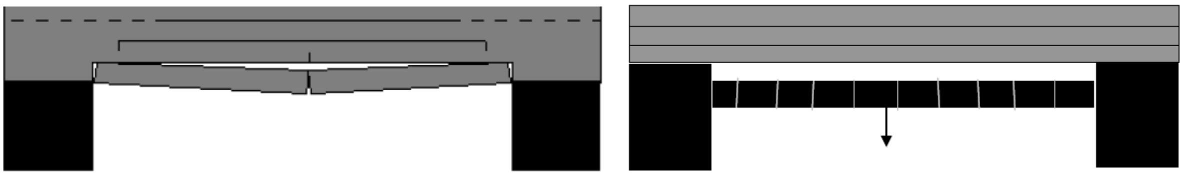

Figure 3: (a) Span delamination and snap-through (after Duncan Fama *et al.*, 2001), (b) Coal beam shear failure (after Duncan Fama *et al.*, 2001)

In terms of empirical tools, the application of Rock Mass Rating (RMR) as an initial assessment tool was reported in Jim Bridger Mine in the USA (Vandergrift *et al.*, 2004). In Australia, the Moura Mine utilised the RMR as well as the Coal Mine Roof Rating (CMRR) (Hoelle 2003) to analyse the roof span stability.

They suggested that once the potential span instability is estimated after the initial assessment, the appropriate actions should be taken. One is to leave coal in the roof (Duncan Fama *et al.*, 2001), or cut some of the immediate weak roof with coal to prevent the roof falls (Fan, 2015). Otherwise, an alternative mining system such as auger system can be considered as auger system tolerates most adverse roof conditions (Duncan Fama *et al.*, 2001).

OTHER DESIGN ISSUES

Other relevant design issues, such as highwall mining through old auger holes, multiple seam mining interactions and backfilling are discussed in the literature. It is suggested that backfilling can be a solution to facilitate highwall mining through old auger holes and thick seam mining, which may be of interest to Australian coal miners considering using a highwall mining system.

Highwall mining through old auger holes

In the USA, about 20% of the highwall mining operations recovered the coal in areas where auger mining was already conducted (Zipf and Bhatt 2004). Highwall mining through old auger holes provides additional opportunities to recover as old auger holes were rarely driven up to 60 m and usually no more than 30 m (Amick 2007). The current CHM systems can drive with the average of 300 m and up to 500 m. NIOSH used numerical modelling to estimate the strength of web pillars containing old auger holes, which is generally reduced to at least 15% to 25% compared with the strength of solid web pillars (Zipf and Mark 2005).

When mine design is carried out in these situations, the reduced strength of web pillars containing auger holes leads to the increase in the web pillar width, resulting in low recovery. In this case, backfilling of the previous auger holes may be considered as an alternative. In a case study, the calculated extraction ratio was largely increased to 65% with backfilling method from 40% without filling the old auger holes; the backfilling was successfully tried in a few holes though (Amick 2007).

Multiple seam highwall mining

When thick seams exceed the working height of the highwall mining equipment or a thick seam splits into thinner seams, multiple seam mining approach can be considered (Ross *et al.*, 1999; Zipf and Mark 2005). The ideal situation in multiple seam highwall mining is to accurately stack upper and lower seam pillars through the entire penetration, which is difficult to be carried out without guidance systems on the highwall miner (Zipf and Mark 2007). In the worst case scenario, when the upper pillars are located at the mid-span of underlying interburden, the interburden thickness is of paramount importance (Zipf 2006). If two working seams are not separated sufficiently, the two seams interact and the strength of the two-layer system is less than the individual strength (Zipf and Bhatt 2004). The interburden thickness of less than 4 m, which is approximately equivalent of one highwall mining entry, is regarded as critical (Zipf and Mark 2005). Figure 4 represents the likely pillar-beam failure mechanism in the worst case scenario where the tensile fracture can occur in the lower part of interburden beam (Zipf 2006).

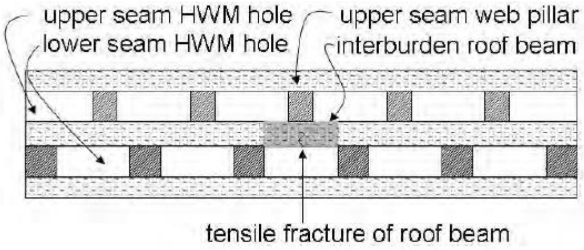

Figure 4: Pillar-beam failure mechanism (after Zipf 2006)

Even if the pillars are perfectly aligned by accurate stacking through the entire penetration, the "tall pillar failure mechanisms" (i.e., combined thicknesses of the seams) (Figure 5) should be considered (Zipf 2006). In this case, Zipf (2006) suggested a combined height of two seams plus interburden for pillar design due to the possibility of weak interburden failure. Zipf (2006) also mentioned that the strength of those tall pillars is 20% to 30% less compared with the strength of the single upper or lower pillar, which may pose risks of pillar and highwall failures.

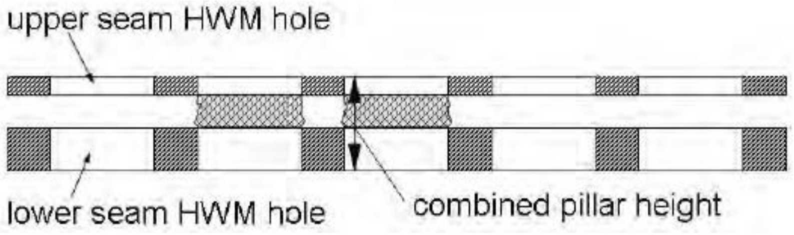

Figure 5: Tall pillar failure mechanism (after Zipf 2006)

Backfilling

Extensive research on the geomechanics of backfill has been carried out over 30 years (Clark and Boyd 1998). However, it had not been widely applied in the Australian coal mining industry due to the perception that backfill was not economically viable at prevailing coal prices (BFP Consultants 1997). In general, the research from BFP Consultants suggested a number of backfill materials, the effectiveness of partial filling and partial recovery rather than complete backfilling and the practical aspects of how to place fill materials (Hume and Searle 1998). The other research from MINSERVE (1999) suggested that in a thick seam, coal recovery may be significantly improved by backfilling. While the recovery rate of a 8 m thick seam highwall mining was to be 30% without backfilling, for example, field trials of two-pass highwall mining with backfilling the lower pass demonstrated that the recovery of up to 64% was achievable when coal seams are greater than 4 m (MINSERVE 1999).

SUMMARY AND CONCLUSION

This paper reviewed the highwall mining experience, including the history of highwall mining from the USA in the 1940s and the introduction into Australia in the 1990s. The geotechnical considerations in highwall mining involving slender and rectangular shape of pillars, unsupported roof span, highwall stability, water and gas considerations are discussed. Design practice for highwall mining is summarised by presenting various approaches for panel/pillar stability and span stability analysis. The relevant design issues for future research topics and challenges such as highwall mining through old auger holes, multiple seam highwall mining and backfilling are also discussed. Some of open cut mines may be able to consider adopting highwall mining as an alternative mining system, on the basis of an understanding of some of the features, the geotechnical considerations and the relevant issues of highwall mining.

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