International Journal of Surface Mining, Reclamation and Environment
Vol. 19, No. 3, September 2005, 188–217

Taylor & Francis
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Ground control for highwall mining in the United States

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Highwall mining is an important coal mining method in the USA and may account for approximately 4% of total USA coal production. Highwall stability is the major ground-control-related safety concern in highwall mining. Engineering away the safety risk by decreasing the highwall slope angle may be the best solution to the hazard posed by vertical joints in highwalls. The Mine Safety and Health Administration (MSHA) requires a ground control plan that usually specifies the hole width, maximum hole depth, maximum overburden depth, seam thickness, web pillar width, barrier pillar width and number of holes between barriers. Design charts for these parameters are given. Web pillars containing pre-existing auger holes are analysed and a design chart for estimating their minimum width is also presented. Close-proximity multiple-split highwall mining, which caused several serious highwall failures, is analysed and recommendations are made. Finally, this study examined records from 5289 highwall miner holes with a total completed hole length of 780 300 m to understand the reasons for early pull out. Average loss was almost 20% of planned hole length, and only 35% of the holes reached the planned depth.

Keywords: Coal mining; Highwall mining; Ground control; Slope stability; Pillar design; Safety

1. Introduction

1.1 *Evolution of auger and highwall mining in the USA*

Auger and highwall mining continues to grow in importance as a coal production method from surface mines in the USA. Volkwein *et al.* (1995) review the evolution of auger and highwall mining systems in the USA, including the earliest augers dating from the mid 1940s, early highwall mining concepts such as the 'Carbide Miner', the 'Push-button Miner', the 'Edna Miner' and the 'Metec Miner' and finally several continuous haulage concepts such as Consol's 'Tramveyor' and

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International Journal of Surface Mining, Reclamation and Environment
ISSN 1389-5265 print/ISSN 1744-5000 online © 2005 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/13895260500165353

Arch Coal's 'Archveyor'. Numerous articles in *World Coal* and *Coal Age* magazines discuss recent developments in the technique.

According to Walker (1997), at least 150 auger units are still at work throughout coal fields in the eastern USA. Two major manufacturers dominate the current auger business. Salem Tool (Salem Tool, Inc., London, KY, USA) provides single-, double- and triple-flight augers with diameters up to 0.85 m (33 in.) capable of depths up to about 122 m (400 ft). BryDet Development Company (http://www.brydet.com) concentrates on larger single-flight augers up to 1.83 m (72 in.) in diameter capable of up to about 244 m (800 ft) depth. While production from auger mining may have declined somewhat, it remains an important coal production tool and continues to develop in capability.

Metec (Walker 1997) introduced the first true highwall miner in 1981. The machine featured a borer-type mining head and twin counter-rotating auger flights to move mined coal out of the hole. In 1996, the Superior Highwall Miner Company (http://www.shm.net) (Walker 2001, Jessey 2002) succeeded Metec. Figure 1 shows a recent Superior Highwall Miner. In its present design, the miner head is a modified Joy Mining Machinery (http://www.joy.com) miner that feeds a series of 6.1 m long (20 ft) pushbeams containing counter-rotating augers for coal transport. Force on the cutter head comes from the launch vehicle at the surface and is transmitted via the pushbeams. Maximum penetration depth is approximately 305 m (1000 ft). The system relies on the rigidity of the pushbeams to maintain proper hole alignment.

Mining Technologies Inc. (MTI) (http://www.addcarsystem.com) built the first Addcar highwall miner system in 1990 to compete with the Metec miner (Walker 1997, Anonymous 1998, Walker 2001, Fiscor 2002, Arrowsmith 2003). Figure 2 shows a typical Addcar system in operation. MTI developed its own highwall miner heads that are similar to conventional continuous miners. The miner head discharges onto a series of 12.2 m long (40 ft) cascading

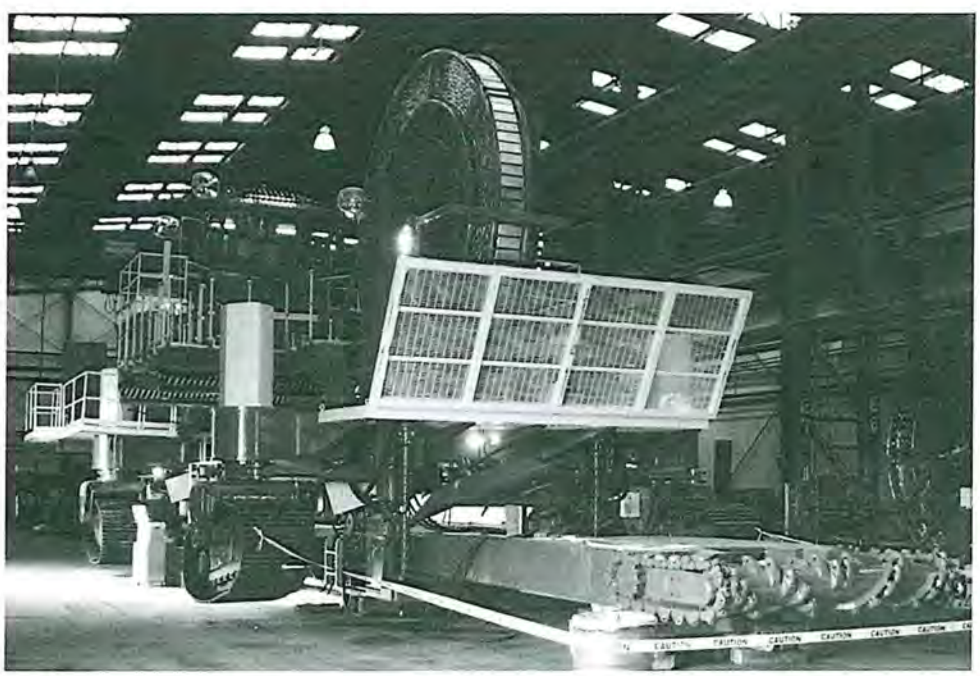


Figure 1. Superior Highwall Miner under construction. Note thin seam cutter head, control cab and cable reel.

Figure 2. Addcar Highwall Miner in operation. Note Addcar in launch vehicle, control cab and discharge conveyor.

conveyor sections known as the Addcars. Force on the miner head comes from crawler trams, thus enabling greater penetration depths and limited direction control while in the hole. Penetrations up to 488 m (1600 ft) have been achieved. As with the Superior Highwall Miner, initial alignment of the Addcar launch vehicle controls the highwall miner hole direction, although limited lateral navigation of the Addcar miner head is feasible. Addcar systems are equipped with cameras that allow the operator to view face conditions, and the latest models feature a gyroscopic guidance system (HORTA) for improved navigational control.

Although the Superior and Addcar Highwall Miners currently dominate the US highwall mining industry, several other companies have also developed noteworthy highwall mining technology. In the early 1990s, Arch Coal developed the Archveyor system (Walker 1997), which used a Joy continuous miner coupled to a self-advancing Klockner–Becorit continuous haulage system. Recently, Rahco International introduced the NexGen system (http://www.nexgen-hms.com) and its first unit was placed in operation in the central Appalachians (Schafer 2002). The NexGen highwall miner addresses the entrapment and resource recovery problem with a unique guidance system that minimizes the likelihood of cutting into adjacent holes, which is a common reason for a trapping roof fall.

1.2 *Production estimates for auger and highwall mining*

Unfortunately, there is a lack of detailed information on current production and manpower for auger and highwall mining activities in the USA. Most auger and highwall mining is conducted within an operating surface mine, and there is no way to separate the auger and highwall mining component from the surface mining production and manpower data. However, recent changes in Mine Safety and Health Administration (MSHA) reporting requirements may provide this information. Because auger and highwall miners are very mobile and move frequently between mine properties, MSHA began issuing mine identification numbers to individual auger and highwall mining machines (MSHA 2003). Having separate mine IDs may enable more accurate estimates of production and manpower for this important mining method.

Table 1 provides estimates of the number of mining machines, productivity and estimated total production in the USA for 2003. Total auger and highwall mining production could be as high as 65 000 000 raw tons. Estimates are that 80% of the highwall miners are operating in the central Appalachian coal fields, mainly in southern and central West Virginia (MSHA District 4) and eastern Kentucky (MSHA Districts 6 and 7). This raw tonnage may reduce to about 45 000 000 clean tons, which is about 4% of total US coal production.

2. MSHA incident statistics for auger and highwall mining

Researchers at NIOSH Pittsburgh Research Laboratory polled the MSHA accident/injury/illness (AII) file for all incidents under auger/highwall mining operations within surface coal mines. In the 20-year period from 1983 to 2002 the search identified 605 incidents reportable to MSHA at auger and highwall mining operations distributed as follows:

- fatalities
- non-fatal days lost injuries (NFDL)
- no days lost injuries (NDL).

Figure 3 shows the accident/injury/illness classification breakdown of these 605 incidents. Handling material such as auger flights or other heavy objects is the most frequent source of accident or injury (24%). Slips and falls in the work environment (20%) and machinery (16%) are other prominent sources. Groundfalls accounted for 70 (12%) of the MSHA-reportable incidents. Close examination of the 70 groundfall-related incident reports shows that approximately three quarters of the incidents resulted in serious days lost injuries. In fact, more than two thirds of these incidents resulted in at least a week off work to recover, and more than half the victims required one month for recovery from their injuries. Also noted are that seven of the groundfall incidents in the MSHA database were large highwall collapses that fortunately did not result in any injuries. Anecdotal evidence suggests that many other near misses occur due to groundfalls that are not documented by anyone.

Examination of the AII classification distribution for the nine fatalities that occurred in auger and highwall mining from 1983 to 2002 provides another view of the risks associated with auger and highwall mining. Figure 4 shows that three of the fatalities were caused by groundfall due to collapse of part of the highwall. Powered haulage (2), machinery (1) and other causes (3) accounted for the remaining fatalities. Based on the distribution of fatal accident classifications,

Table 1. Estimated auger and highwall mining production for 2003.

Machine	Approximate number in operation	Production per machine (raw tons per year)	Total production (raw tons)
Superior Highwall Miners	30	650 000	20 000 000
Addcar Highwall Miners	30	1 000 000	30 000 000
Augers	150	100 000	15 000 000
TOTAL (raw tons)			65 000 000
TOTAL (clean tons)			45 000 000

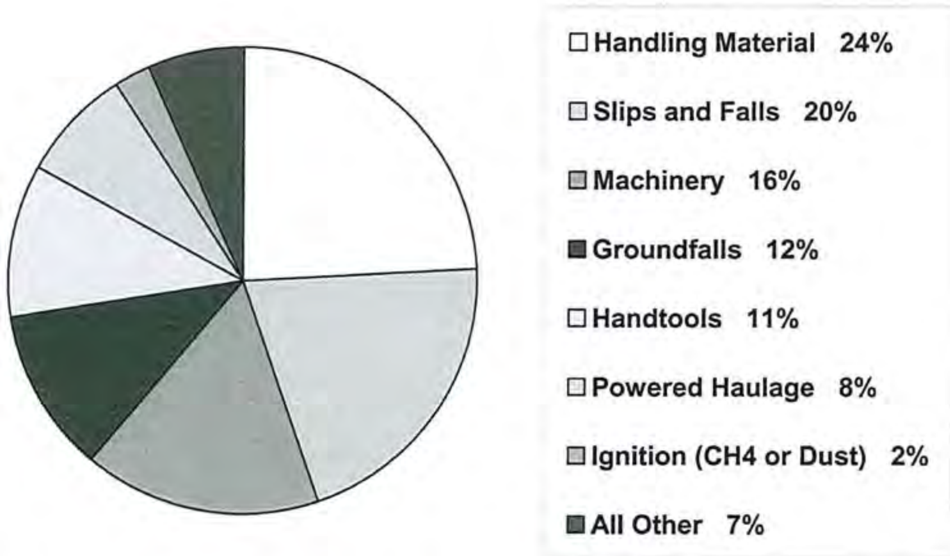


Figure 3. Distribution of 605 incidents in auger and highwall mining from 1983–2002.

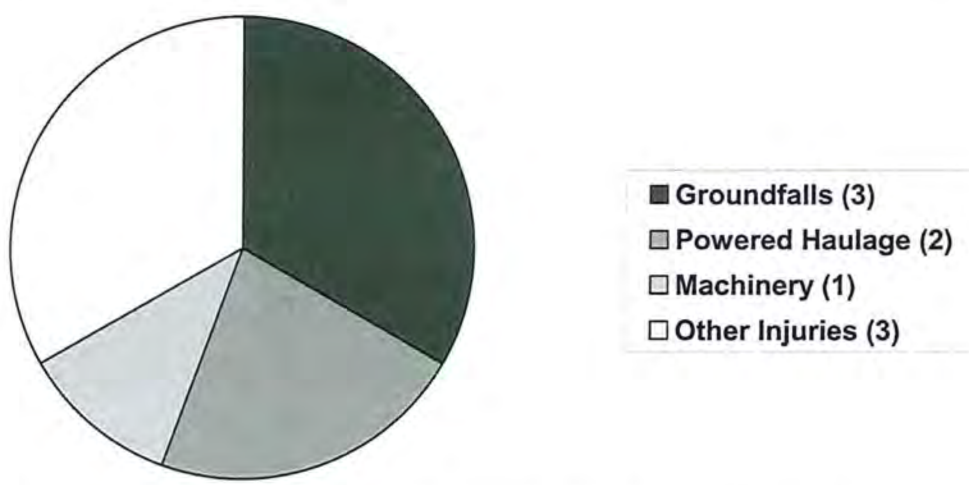


Figure 4. Distribution of nine fatality causes in auger and highwall mining from 1983–2002.

ground control and in particular highwall stability, along with powered haulage and machinery accidents, appear to pose the major risks. Overall, the fatality and injury rates for highwall mining are approximately the same as for surface coal mining and are considerably lower than those as a result of underground coal mining.

3. Ground control safety concerns in highwall mining

By far the overriding ground-control-related safety concern in highwall mining is highwall stability (Shen and Duncan-Fama 2001, Adhikary *et al.* 2002, Gardner and Wu 2002, Zipf and Bhatt 2004). As discussed in the previous section, three of the nine fatalities connected with auger and highwall mining in the last 20 years were caused by highwall collapse, and the only fatality that occurred in the last five years at highwall mining operations was again due to highwall collapse. Ensuring highwall stability through proper ground control engineering is thus of paramount importance to safe highwall mining operations. Two major factors affect highwall stability—geologic structure and pillar stability.

In the central Appalachians, where the majority of highwall mining occurs in the USA, hillseams are the most prominent geologic structures that affect highwall stability. Hillseams (or mountain cracks) are near-vertical fractures in the rock that are formed in response to natural weathering and erosion of hillsides (Sames and Moebs 1989). They extend from the surface down to several hundred metres. Their orientation is roughly parallel to the hillside, but they can also run across narrow points or ridge lines. They are often accompanied by a secondary set of fractures at right angles to the dominant fracture. Hillseams may cause vertical wedges or long rectangular slabs to separate from the highwall. Figure 5 shows a highwall containing hillseams. A highwall stability safety hazard arises when rock slabs that form along the hillseams detach and fall away from the highwall face. The resulting rock falls can range in size from blocks of less than 1 m^3 to large slabs of more than 1000 m^3. Many highwall mining operations will skip a hole where a hillseam enters the highwall. Where a hillseam is known to run parallel to the highwall face, the entire area between the entry and exit points may be skipped.

Unfortunately, an operator cannot control the location of hillseams or reliably detect their presence within a highwall; however, there are measures that can be taken to minimize the risk of failure associated with hillseams, namely planning, inspection, monitoring, good blasting practices and finally a lower highwall slope angle. Planning can readily decrease the impact of hillseams.

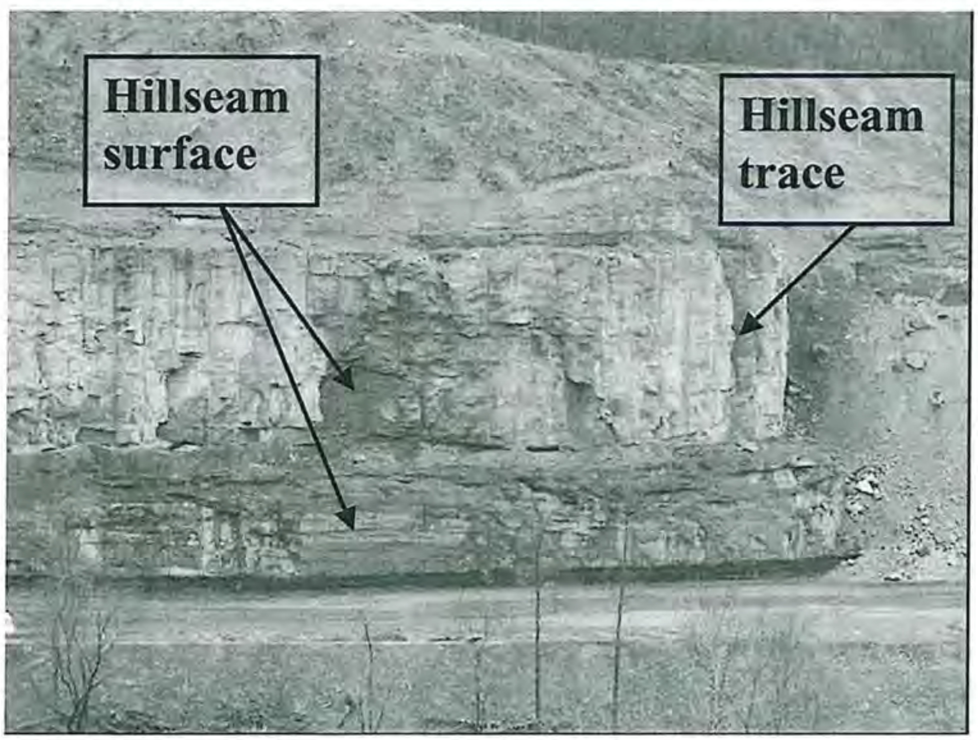


Figure 5. Hillseams indicated by arrows in contour mine highwall. Note that weathering along hillseams can extend several hundred metres or more below the surface.

Most operators choose to skip those areas of the highwall where a prominent hillseam daylights (figure 6). The existence of such areas is known for several weeks in advance of highwall mining; planning engineers can therefore adjust the layout of highwall mining panels to locate barrier pillars within areas of questionable highwall stability.

Daily inspection of the benches above the active highwall mining area can also decrease the risk of highwall failure. Figure 7 shows a crack in a bench immediately above a highwall miner. Simple displacement monitors may be useful for detecting movement along cracks that may precede a significant life-threatening failure.

New tools such as GroundProbe's Slope Stability Radar (http://www.groundprobe.com) may also prove useful in detecting the motion of rock slopes above an active highwall mining operation. This device can detect the relative movement of the slope as time progresses. Figure 8 shows a typical displacement map of a large slope surface. If the motion exceeds some threshold, it may trigger a range of responses by the exposed personnel ranging from closer watch to immediate evacuation.

Several well-known blasting practices can decrease blast damage done to the wall rock and preserve the integrity of hillseams contained therein. Most surface coal miners in the central Appalachians utilize pre-splitting and the familiar half-barrels are routinely seen throughout the pits. Cunningham (2000) suggests that a shorter delay along the face and a longer delay between rows will direct more of the blast force parallel to the face, thereby doing less damage to the wall rock. In addition to pre-splitting, decreasing the burden, spacing and charge weight in drill holes close to the highwall will also decrease damage to the wall rock.

Finally, decreasing the highwall slope angle from 90° (vertical) to 70° – 80°, especially in areas of known hillseam concentration, may eliminate entirely most of the hazard due to slope failure

Figure 6. Daylighting hillseam.

Figure 7. Crack in bench above highwall mining operation.

Figure 8. Slope face displacement map produced by GroundProbe's Slope Stability Radar.

along hillseams. Figure 9(a) is a sketch of a typical vertical highwall containing a hillseam. Sliding or toppling failure along the hillseam is very possible. However, by decreasing the slope angle to about 70°, much of the hazard is eliminated completely, as shown in figure 9(b). The uppermost part of the hillseam block is removed and the base of that block is braced against failure. Decreasing the highwall slope angle does not necessarily have an adverse impact on overburden removal or overall coal recovery. Granted, coal recovery from the surface mining operation could decrease somewhat; however, much of this coal may be recovered during subsequent highwall mining. The mine operator should seek to maximize safety and productivity from the entire mining operation and not just the surface mining and highwall mining components. Sacrificing some apparent efficiency in the surface mining component may improve efficiency in the highwall mining component for a net gain in the whole system.

The second factor related to highwall stability is the stability of web and barrier pillars (Medhurst 1999, Zipf 1999, Shen and Duncan-Fama 2001, Adhikary *et al.* 2002, Gardner and Wu 2002, Vandergrift *et al.* 2004,). Web pillar failure and the subsequent subsidence of the overlying rock can destabilize the highwall face. Figure 10 shows one large failure (Zipf 1999). In this case, 30 to 50 web pillars failed suddenly, which caused substantial rock fall from the highwall. The rock fall was sufficient to completely bury a 100 tonne coal haulage truck. Fortunately no one was in the pit when this failure occurred. Figure 11 shows another area where web pillar failure led to large rockfalls from the highwall. In this case, the operator was engaged in close-proximity multiple-seam mining where the lower seam split is mined first, followed by partial backfilling of the pit and mining of the upper seam split. The web pillar collapse also trapped the highwall miner which required several months' effort to recover.

An additional ground-control-related safety concern with highwall mining is a 'stuck' or trapped highwall miner and the ensuing retrieval or recovery operation. Anecdotal evidence suggests that many trapped highwall miners result from a ground control problem such as:

- roof fall
- web pillar failure (ride, squeeze)
- floor failure in multiple-lift mining
- excessive span due to crossed holes.

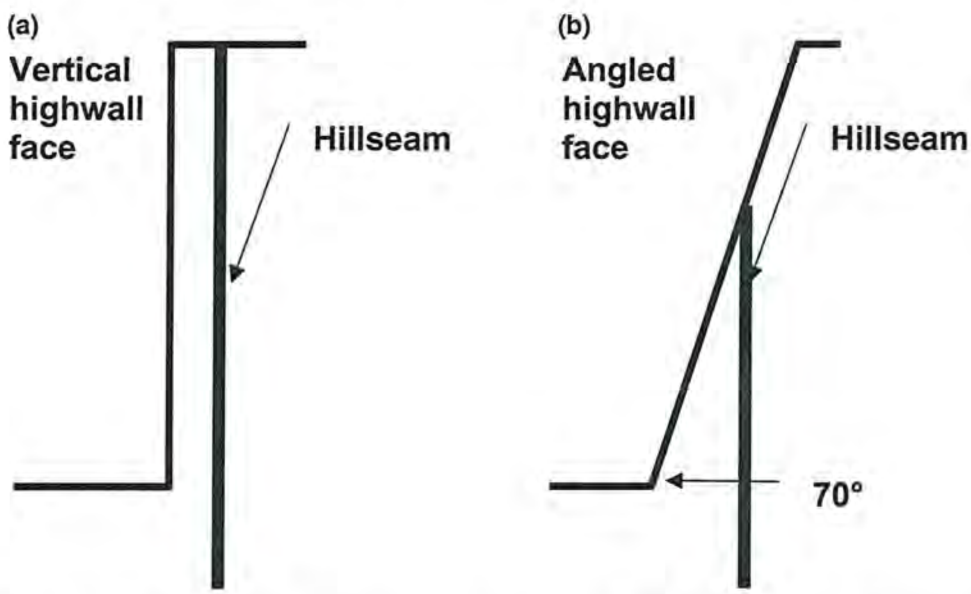


Figure 9. Vertical highwall containing hillseam (a) and 70° highwall with hillseam (b).

Figure 10. Site of massive web pillar collapse resulting in highwall slope failure. Photograph is taken from adjacent spoil pile. Highwall is about 50 m (150 ft) high. A 100 tonne (110 ton) coal haulage truck is buried in rockfall debris.

Roof rock quality is frequently the cause of a roof fall that results in a trapped highwall miner, and it also influences the success in their retrieval. An operator is more likely to pull out a trapped highwall miner under a shale roof than under a strong sandstone roof as weak shale breaks up more easily than strong sandstone during the pull out.

Many trapped highwall miners also result from rolls. Undulations of the coal seam or a change in seam pitch may cause tight spots that can trap a highwall miner during withdrawal.

When a highwall miner gets trapped, several options exist as listed below in order of increasing difficulty and decreasing frequency of use. There are safety hazards to be aware of with each.

- surface retrieval (pull out)
- surface excavation
- underground recovery

Surface retrieval is by far the least complicated option. Many operators have built special devices to hook onto separated equipment in the hole. The operator pulls on the trapped highwall mining equipment with anything available such as the launch vehicle, dozers, loaders or haul trucks. The major hazards associated with surface retrieval are the tight cables and connectors used during the pull.

Excavating from the surface may be the safest option since the major hazard is again highwall stability. However, removing at least 100 000 m^3 of rock is not uncommon. Furthermore, during excavation, the trapped equipment is likely to become damaged due to nearby blasting.

Figure 11. Highwall failure in close-proximity multiple-seam mining area.

Underground recovery is arguably the most hazardous and essentially requires the set up of a small underground coal mining operation. MSHA requires the operator to submit a recovery plan to the District Manager that must be reviewed and approved prior to the start of underground recovery.

Interviews with MSHA roof control specialists suggest that about 10 to 15 highwall mining systems became seriously trapped during 2003 and required a substantial retrieval effort such as underground recovery, surface excavation or a major surface retrieval. If there were about 60 highwall miners operating in 2003, then it seems that about 1 in 4 became trapped during that year and required a major recovery/retrieval effort.

4. Analysis of MSHA highwall mining ground control plans

MSHA recognizes the ground-control-related safety concerns associated with highwall mining and has required each portable auger or highwall mining operation to develop and follow 'an appropriate highwall ground control plan, which addresses the web spacing and other measures necessary to safely conduct the high rates of recovery'. (MSHA 2003) Various MSHA Coal Mine Safety and Health Districts provided NIOSH-PRL researchers with 40 highwall mining ground control plans. Most of the plans (80%) came from the central Appalachians in Kentucky and West Virginia, and most (again 80%) were dated 2002–2004. As expected, about half the plans specified use of a Superior Highwall Miner and the other half planned to use an Addcar system. The number of plans from MSHA is somewhat lower than the number of highwall miners in operation as estimated in table 1; however, this minor shortfall does not detract from our conclusions.

From these 40 plans, 51 distinct cases were compiled from which to evaluate highwall mining designs. Figure 12 shows the distribution of maximum seam thicknesses and maximum cover depths considered in the plans. In three quarters of planned highwall mining, maximum seam thickness is between 0.9 and 1.8 m (3–6 ft). Relatively few highwall miners (less than 12%) have planned mining heights greater than 2.1 m (7 ft). Most of these thicker seam operations are in the western USA in MSHA District 9. In most operations (about 82%), the maximum depth of cover is less than 91 m (300 ft). The rest have a planned maximum depth of cover in the range 91–152 m (300–500 ft). At this time none appears to be operating under more than 152 m (500 ft) of cover, although this could change soon.

Maximum seam thickness and maximum depth of cover are the main inputs for geotechnical design of web pillar width. In about 15% of the plans examined, the Analysis of Retreat Mining Pillar Stability (ARMPS) program (Mark *et al.* 1995) was the analysis method used. Over 25% used another form of a tributary area method for analysis. Past experience was the basis for many designs, but unfortunately, the analysis method could not be identified in most of the highwall

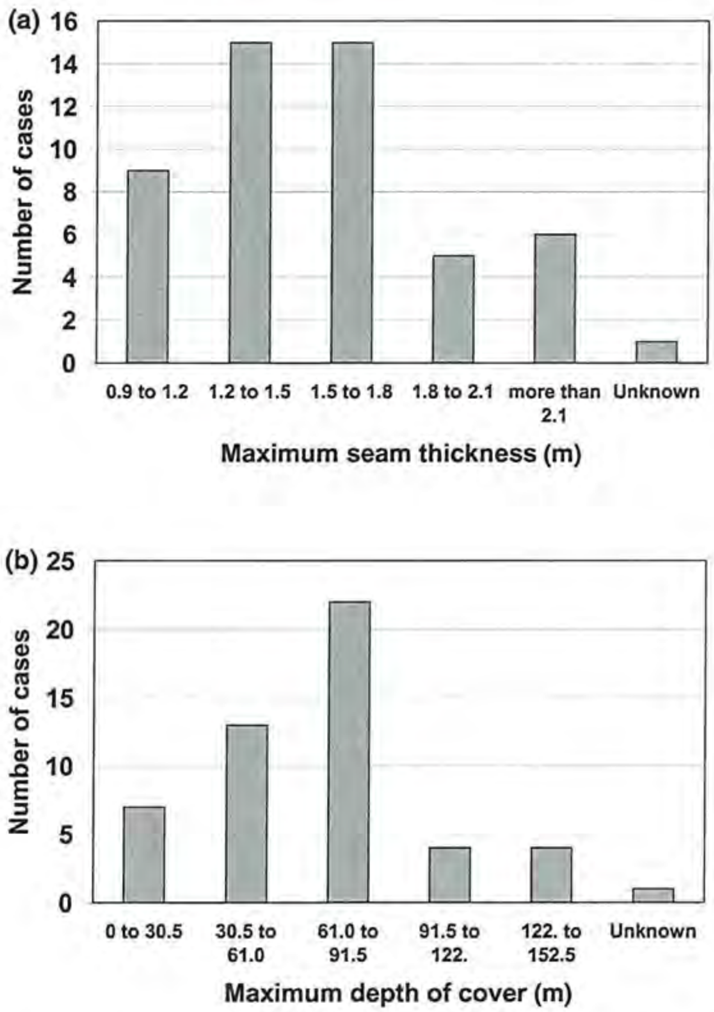


Figure 12. Maximum seam thickness (a) and maximum depth of cover (b) distribution from MSHA highwall mining ground control plans.

mining ground control plans examined. As shown in figure 13(a), the minimum web width specified in the plans ranged from 0.9–2.1 m (3–7 ft) in over 82% of the cases. More important for stability is the width-to-height (*W*/*H*) ratio of these web pillars. Figure 13(b) shows that *W*/*H* is in the 1–1.25 range for about 50% of the cases, while it is between 0.5–1 in 25% and more than 1.25 in the remaining 25% of cases. In general, keeping the web pillar *W*/*H* ratio above 1 is desirable to maintain better web pillar integrity. Designs with *W*/*H* less than 0.5 were not encountered.

Figure 13(c) shows estimates of the web pillar stability factor based on data provided in the ground control plans. The estimates used the tributary area method to calculate pillar stress and the Mark–Bieniawski formula (Mark *et al.* 1995) to calculate the strength of a strip pillar assuming a coal strength of 6.2 MPa (900 psi). In 45% of the cases, it appears that the stability factor exceeded 1.6, while in 31% of cases, the stability factor appeared to range from 1.3–1.6. Thus, in over three quarters of the cases examined, a satisfactory web pillar stability factor most likely exists. However, in a few circumstances (about 8%), the stability factor may be in the range 1–1.3, while in another 8% of cases the stability factor was apparently slightly less than 1. These stability factor estimates from the ground control plans are estimates only, and judgment of individual plans is not implied.

Figure 14(a) provides data on minimum barrier pillar width found in the plans. Most barriers appear to range in width from 3–7.6 m (10–25 ft), but in almost half the cases a firm dimension on barrier pillar width was not specified. In most cases, the reasoning behind the barrier pillar width was unknown. Experience-based design rules were employed in some cases. For example, about 15% of the plans sized barrier pillars as one web pillar width plus one hole width, while another 15% used two web pillar widths plus one hole width. In about 10% of the cases, barrier pillar widths were designed using the tributary area method with a stability factor of one and the assumption that all web pillars in a panel have failed.

Figure 14(b) shows data on the *W*/*H* ratio of highwall mining barrier pillars. Unfortunately there was no information in about one third of the cases considered. However, when data were available, the *W*/*H* ratio was 3 or more in about two thirds of the cases and less than 3 in the remaining third. For stability reasons, a barrier pillar with a *W*/*H* ratio above 3 has sound geomechanics-based advantages (Zipf 1999).

Figure 14(c) presents data on the number of highwall miner holes between barrier pillars. When information is available, it appears that about 37% of the plans specify no more than 20 holes between barrier pillars, 44% specify 10 holes and 15% require as few as 5 holes between barrier pillars. Comment on the number of holes between barrier pillars is reserved for later discussion.

5. Ground control analysis of highwall mining layouts

When designing a highwall mining layout, the mining engineer must specify: (1) the web pillar width; (2) the number of web pillars between barrier pillars; (3) the barrier pillar width. The design parameters are determined by the highwall miner hole width, the mining height and the overburden depth. In addition, the mine planner must estimate the pillar strength, the applied stress on pillars and the pillar stability factor.

5.1 *Coal pillar strength*

Numerous empirical formulas are available to predict coal pillar strength; however, the Mark–Bieniawski (Mark *et al.* 1995) formula applies best for web pillars, which are very long, narrow

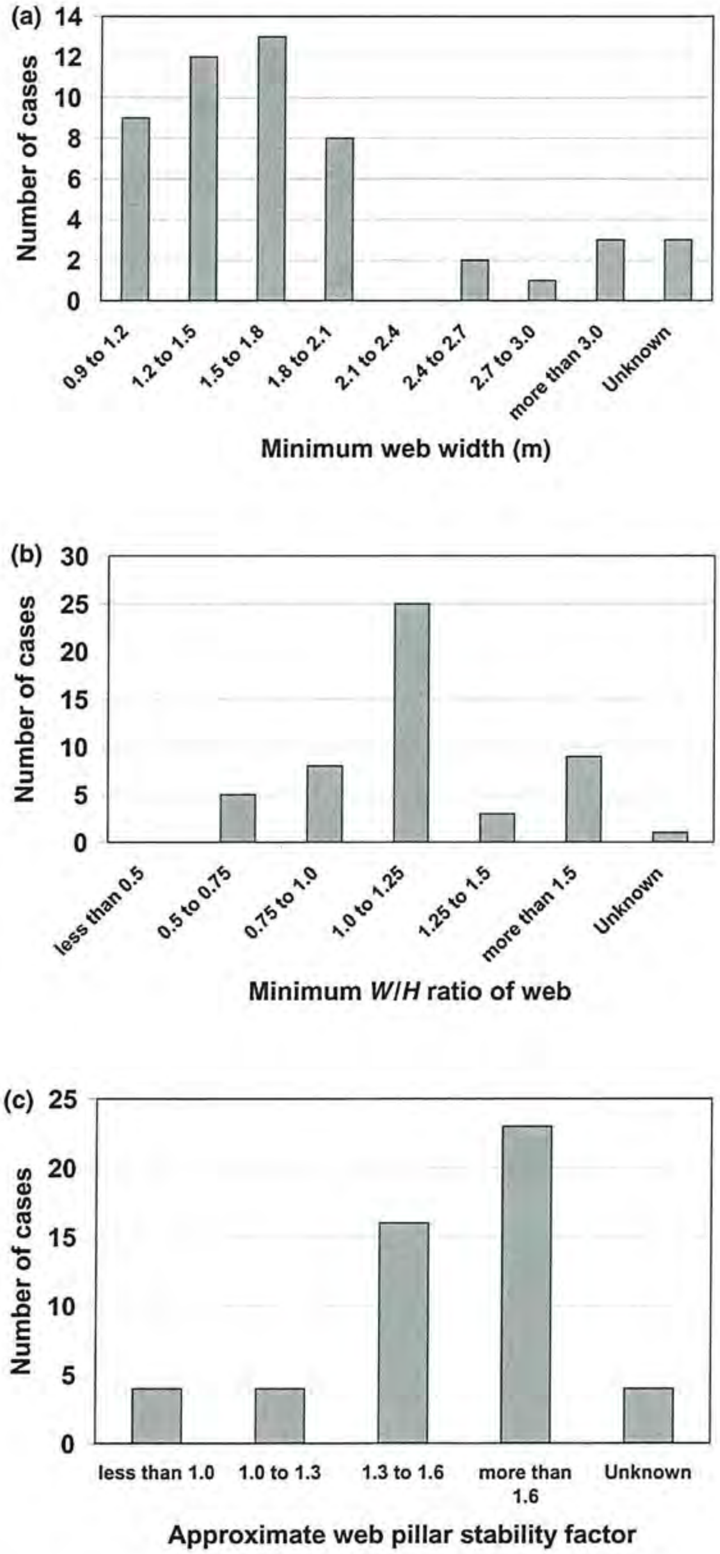


Figure 13. Minimum web pillar width (a), minimum width-to-height (*W*/*H*) ratio (b) and approximate web pillar stability factor (c) from MSHA highwall mining ground control plans.

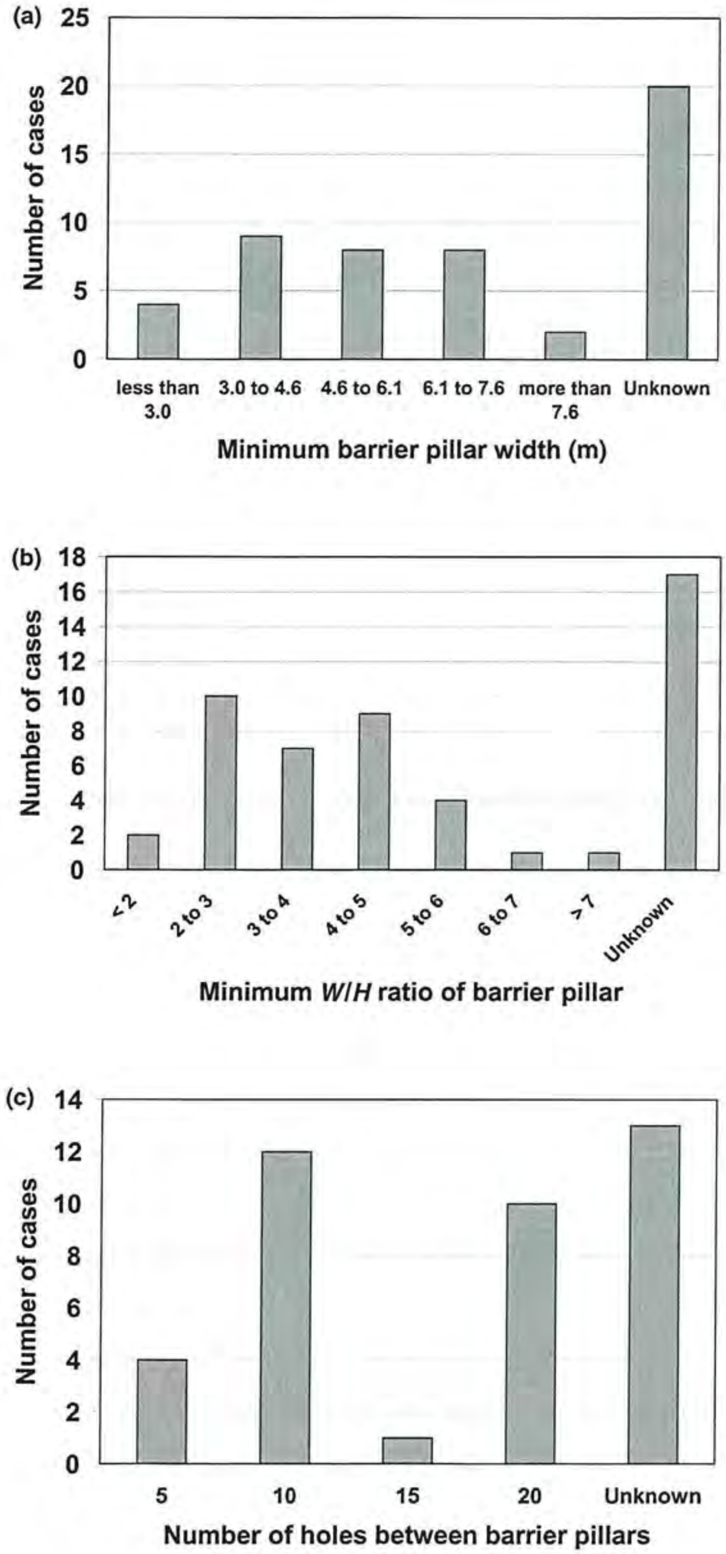


Figure 14. Minimum barrier pillar width (a), minimum width-to-height (*W*/*H*) ratio (b) and number of holes between barrier pillars (c) from MSHA highwall mining ground control plans.

rectangular pillars. For long pillars whose length is much greater than their width, the Mark–Bieniawski formula reduces to

$$S_P = S_I(0.64 + 0.54W/H) \quad (1)$$

where S_P is the web or barrier pillar strength, S_I is the in-situ coal strength, W is the web or barrier pillar width and H is the mining height. The in-situ coal strength is normally taken as 6.2 MPa (900 psi). The mining height can be equal to the seam thickness, but it may be greater if some rock is mined along with the coal.

5.2 *Coal pillar stress*

The tributary area method is the simplest for estimating the vertical stress on web and barrier pillars. The average vertical stress on a web pillar is given by

$$S_{WP} = S_V(W_{WP} + W_E)/W_{WP} \quad (2)$$

where S_{WP} is the vertical stress on web pillar, S_V is the in-situ vertical stress, W_{WP} is the web pillar width and W_E is the highwall miner hole width.

The highwall mining equipment dictates the hole width, which varies from 2.7–3.6 m (9–12 ft). In-situ vertical stress depends on the overlying rock density and overburden depth. Vertical stress gradient is typically 0.025 MPa/m (1.1 psi/ft). Overburden depth may be taken as the maximum overburden depth on a highwall mining web pillar, which is the most conservative, or alternatively as a high average value computed as

$$D_{Design} = 0.75 \times D_{MAX} + 0.25D_{MIN} \quad (3)$$

where D_{Design} is the design overburden depth, D_{MAX} is the maximum overburden depth and D_{MIN} is the minimum overburden depth.

Finally, the stability factor for web pillars against strength failure is simply

$$SF_{WP} = \text{web pillar strength } (S_P)/\text{web pillar stress } (S_{WP}) \quad (4)$$

If the number of web pillars in a panel is selected as N, then the panel width (W_{PN}) is given by

$$W_{PN} = N(W_{WP} + W_E) + W_E \quad (5)$$

Neglecting the stress carried by the web pillars (i.e. assuming that they have all failed), the average vertical stress on a barrier pillar is

$$S_{BP} = S_V(W_{PN} + W_{BP})/W_{BP} \quad (6)$$

where S_{BP} is the vertical stress on the barrier pillar, W_{PN} is the panel width and W_{BP} is the barrier pillar width. Similarly, the stability factor for barrier pillars against strength failure is simply

$$SF_{BP} = \text{barrier pillar strength } (S_P)/\text{barrier pillar stress } (S_{BP}) \quad (7)$$

Because the stress carried by web pillars within a panel is neglected, the stability factor for barrier pillars can be as low as 1. Figure 14(a) shows that the width of barrier pillars exceeded 5 m (16 ft) in more than half the cases examined and, more importantly, the W/H ratio for barrier pillars (figure 14(b)) exceeded 3 in two thirds of the cases. Barrier pillars with a W/H ratio greater than 3 are superior for sound geomechanics reasons.

The ARMPS program (Mark *et al.* 1995) applies similar relations to the above for estimating the stability factor of web and barrier pillar combinations. When using ARMPS to analyse highwall mining layouts, the mining engineer should consider all the web pillars plus one barrier pillar in the analysis. The loading condition is normally development loading (option 1); however if old underground workings are nearby, alternative loading conditions such as a front gob (option 2) may be necessary.

6. Web and barrier pillar design charts and design example

The above equations for web and barrier pillar analysis can be implemented into a spreadsheet (Zipf 1999) or programmable calculator. In lieu of either, figures 15 and 16 are design charts for web pillars while figure 17 provides design guidance for barrier pillars. Figure 15 applies to a 2.75 m wide (9 ft) highwall miner hole, while figure 16 applies to a 3.66 m wide (12 ft) hole. In figures 15 and 16, parts (a) and (b) apply to stability factors of 1.3 and 1.6, respectively. In figure 17, parts (a), (b) and (c) apply to panel widths of 30.5, 61 and 122 m (100, 200 and 400 ft), respectively. Note that this design chart assumes a barrier pillar stability factor of 1.0 and it neglects any load-carrying capacity of the web pillars with a panel. Compared to ARMPS, these charts always give wider web and panel widths and are therefore conservative.

To use figures 15, 16 or 17, the user begins with the design depth on the x axis, moves up vertically to the applicable mining height and then moves left horizontally to the y axis where the suggested web (or barrier) pillar width is read. Several examples below illustrate the use of these design charts.

Table 2 describes conditions for an example. The operator prefers to leave a barrier pillar after every ten highwall miner holes. The minimum acceptable stability factor for the web pillars is 1.3, and at the highwall itself near the start of the holes the stability factor must exceed 1.6.

To estimate the web pillar size, use figure 16(a) for a hole width of 3.66 m (12 ft) and a stability factor of 1.3. Using the design depth of cover and a mining height of 1.8 m (6 ft), the suggested web pillar width is about 2.4 m (8 ft). This web pillar has a desirable W/H ratio of 1.33 since it is more than 1.

Using figure 16(b), the requirement that the stability factor exceed 1.6 directly under the highwall is checked. For a depth of cover of 30.5 m (100 ft) and a mining height of 1.8 m (6 ft), the minimum web width with a stability factor of 1.6 is about 0.9 m (3 ft). Therefore, the 2.4 m wide (8 ft) web pillar must have a stability factor much greater than 1.6.

The operator plans to leave barrier pillars after every ten holes, so based on equation 5, the panel width is 58.2 m (192 ft). From figure 17(b) for a 61 m wide (200 ft) panel with a design depth of cover of 99 m (325 ft) and a mining height of 1.8 m (6 ft), the suggested barrier pillar width is about 8.5 m (28 ft). The barrier pillar has a desirable width-to-height ratio of 4.66 since it is more than 3. This barrier pillar width happens to equal exactly the common rule-of-thumb for barrier pillar width which is one hole width plus two web pillar widths.

As a check, situation 1 was analysed with ARMPS. The web pillars alone had a stability factor (on development) of 1.32. Adding the 8.5 m wide (28 ft) barrier raised the overall stability factor to 2.21.

7. Special design cases

7.1 *Highwall mining through old auger holes*

Many highwall miners are re-working highwalls that were previously auger mined. A review of MSHA highwall mining ground control plans indicates that at least 20% of the highwall mining operations expect to encounter old auger holes somewhere on a property (Zipf and Bhatt 2004). Figure 18 shows typical highwall mining web and barrier pillars containing pre-existing auger

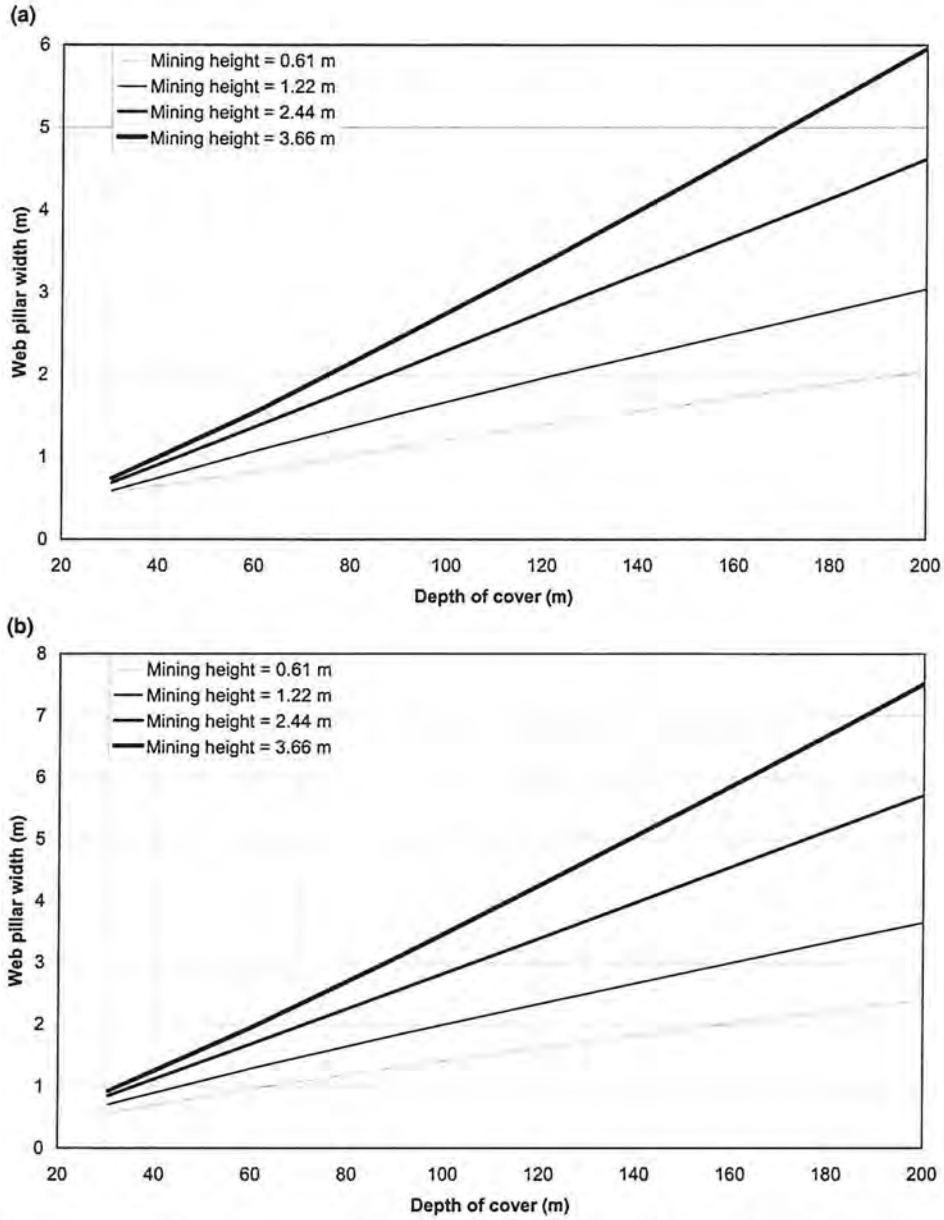
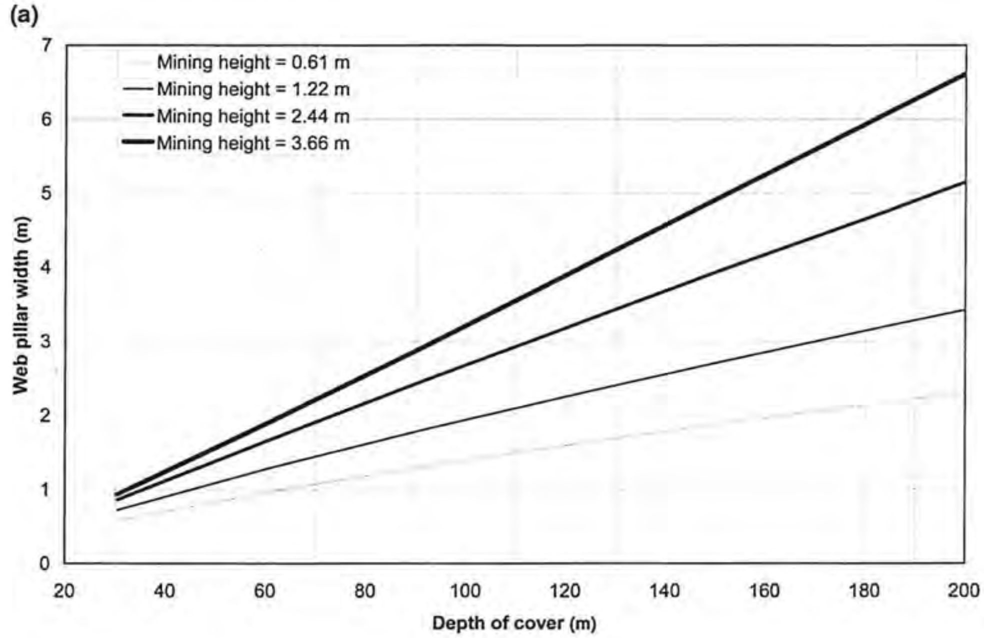


Figure 15. (a) Suggested web pillar width with stability factor of 1.3, coal strength of 6.2 MPa and 2.75-m-wide hole. (b) Suggested web pillar width with stability factor of 1.6, coal strength of 6.2 MPa and 2.75 m wide hole.

holes. From a ground control standpoint, the critical issue is the strength of a highwall mining web pillar that contains a row of auger holes. As mentioned earlier, maintaining stability of web pillars is crucial for maintaining stability of the highwall above the active mining operation. Conventional coal pillar strength formulas do not apply directly to this situation.

To address this issue, NIOSH researchers used numerical models to estimate the strength of highwall mining web pillars containing pre-existing auger holes (Zipf 2005). Three auger hole configurations were considered, namely, 0.6, 0.7 and 0.8 m diameter holes, all on 1 m centres. The



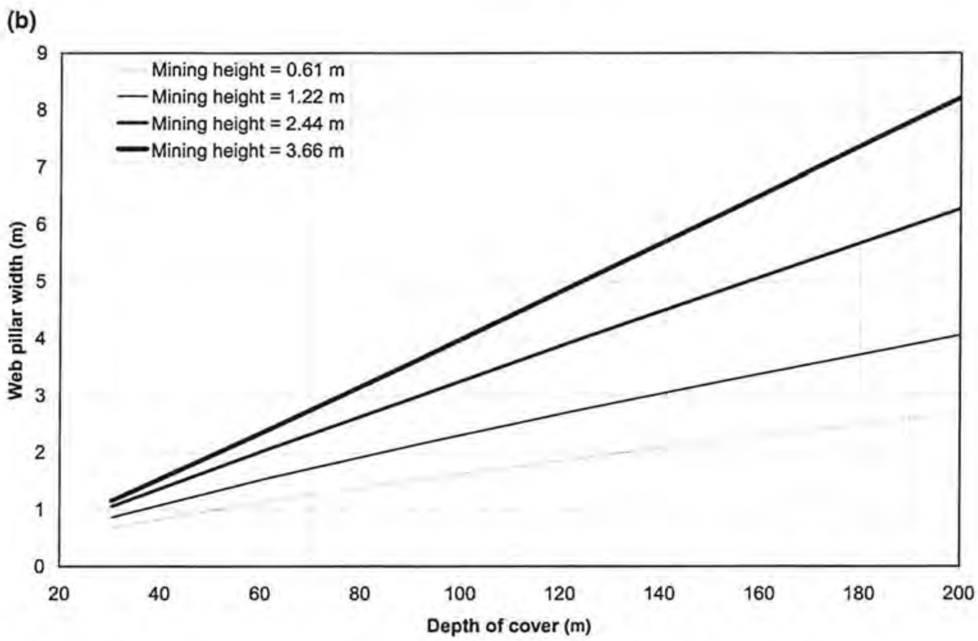


Figure 16. (a) Suggested web pillar width with stability factor of 1.3, coal strength of 6.2 MPa and 3.66 m wide hole. (b) Suggested web pillar width with stability factor of 1.6, coal strength of 6.2 MPa and 3.66 m wide hole.

last configuration follows the common rule-of-thumb in auger mining that recommends an auger web width of one quarter the auger hole diameter.

Table 3 summarizes the auger hole geometries considered and the computed strength of highwall mining web pillars containing auger holes. Using the Mark–Bieniawski formula, the

Table 2. Design example.

Design inputs		
Coal seam thickness		1.8 m (6 ft)
Highwall miner width	3.66 m (12 ft)	
Maximum depth of cover	122 m (400 ft)	
Highwall height	30.5 m (100 ft)	
Design depth of cover (equation (3))	99 m (325 ft)	
Design outputs		
Web width at 99 m for stability factor = 1.3	2.4 m (8 ft)	
Web width at 30.5 m for stability factor = 1.6	0.9 m (3 ft)	
Panel width (equation (5))	58.2 m (192 ft)	
Barrier pillar width at 99 m	8.5 m (28 ft)	

strength of a solid highwall mining web pillar with a W/H ratio of 3 is about 14 MPa (2034 psi). These calculations for a range of practical auger mining geometries indicate that the strength of a highwall mining web pillar containing auger holes is 25% to as little as 15% of the solid web pillar strength.

The numerical calculations also indicated that the strength of a highwall mining web pillar containing auger holes is independent of its W/H ratio. This observation is to be expected for closely spaced auger holes where the strength of the auger hole webs determines the strength of the overall highwall mining web pillar. In most auger mining, the auger web pillars are usually closely spaced and somewhere within the range considered in table 3. If the auger holes are widely spaced with a ratio between auger web width and auger hole diameter that is much greater than 1, then the presence of the auger holes may not affect the highwall mining web pillar as much. In that case, the web pillar strength will increase as its W/H ratio increases.

Based on these reduced highwall miner web pillar strengths that are independent of W/H ratio, the required web pillar width is computed assuming a safety factor of 1.3. The analyses use the simple tributary area method to calculate pillar stress, and the pillar strength is as given in table 3. In most practical situations, the horizontal depth of auger holes is less than 61 m (200 ft) where the depth of cover rarely exceeds 46 m (150 ft). Figure 19 presents a simple chart for estimating the minimum width of a highwall mining web pillar containing auger holes of various configurations. This chart assumes a highwall miner hole width of 3.66 m (12 ft). The user should size these webs to contain at least three intact auger mining webs—hence the design chart begins at a web width of 2 m (6.6 ft). This chart also neglects many other factors that may adversely affect the strength of a highwall mining web pillar containing pre-existing auger holes such as the age of the auger holes, presence of water, low coal strength and other factors. The chart is also based on results of a numerical stress analysis that may not consider all the relevant factors in any given situation. For these reasons, the engineer must use this design chart with caution.

7.2 *Close-proximity multiple-split highwall mining*

Many highwall mining operations recover multiple seams in very close proximity to one another. In the eastern USA, this situation arises frequently when a thick seam splits into thinner seams. In western USA mines, certain very thick seams can exceed the working height of the highwall miner, and a multiple-seam mining approach may be utilized (Ross *et al.* 1999). Multiple-seam mining

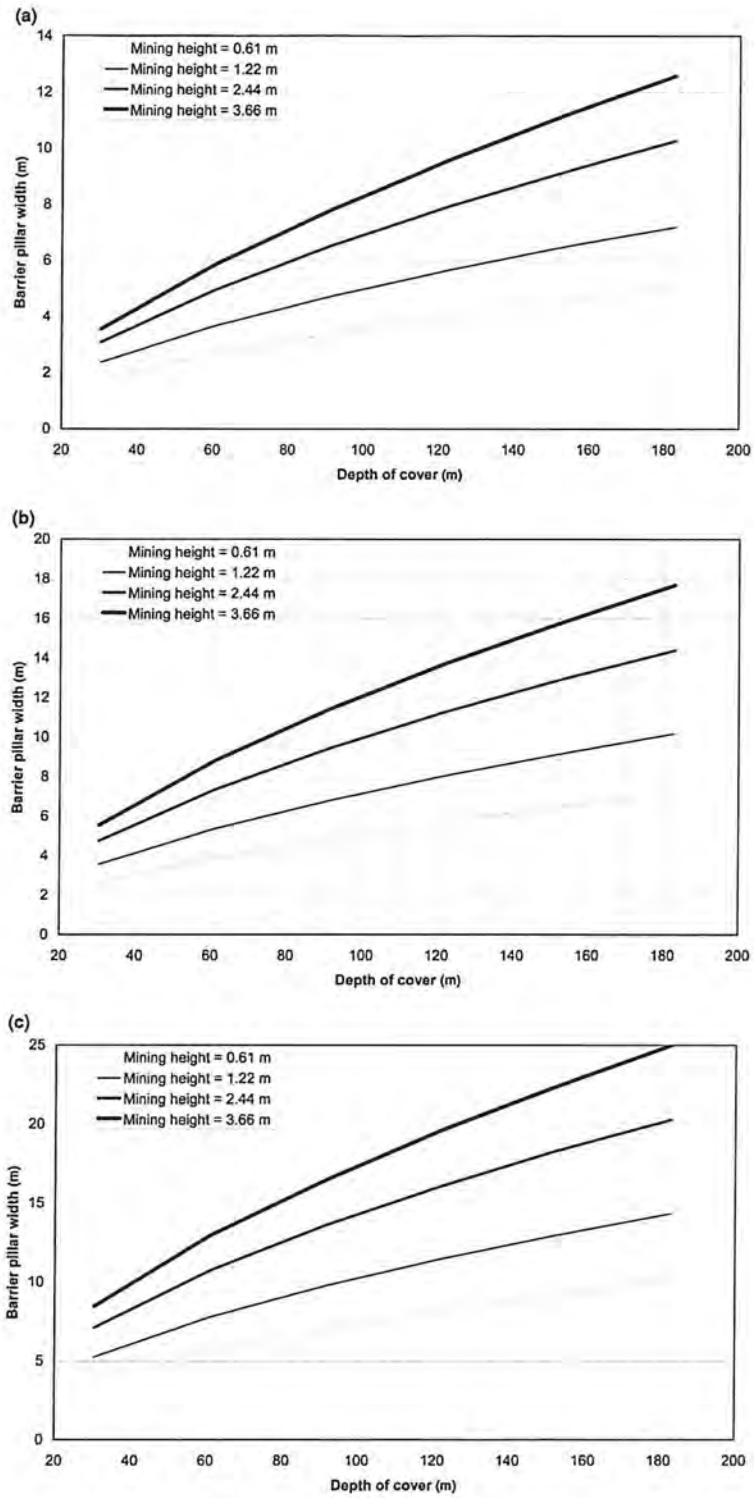


Figure 17. (a) Suggested barrier pillar width for 30.5 m wide panel assuming coal strength of 6.2 MPa and stability factor of 1.0. (b) Suggested barrier pillar width for 61.0 m wide panel assuming coal strength of 6.2 MPa and stability factor of 1.0. (c) Suggested barrier pillar width for 122 m wide panel assuming coal strength of 6.2 MPa and stability factor of 1.0.

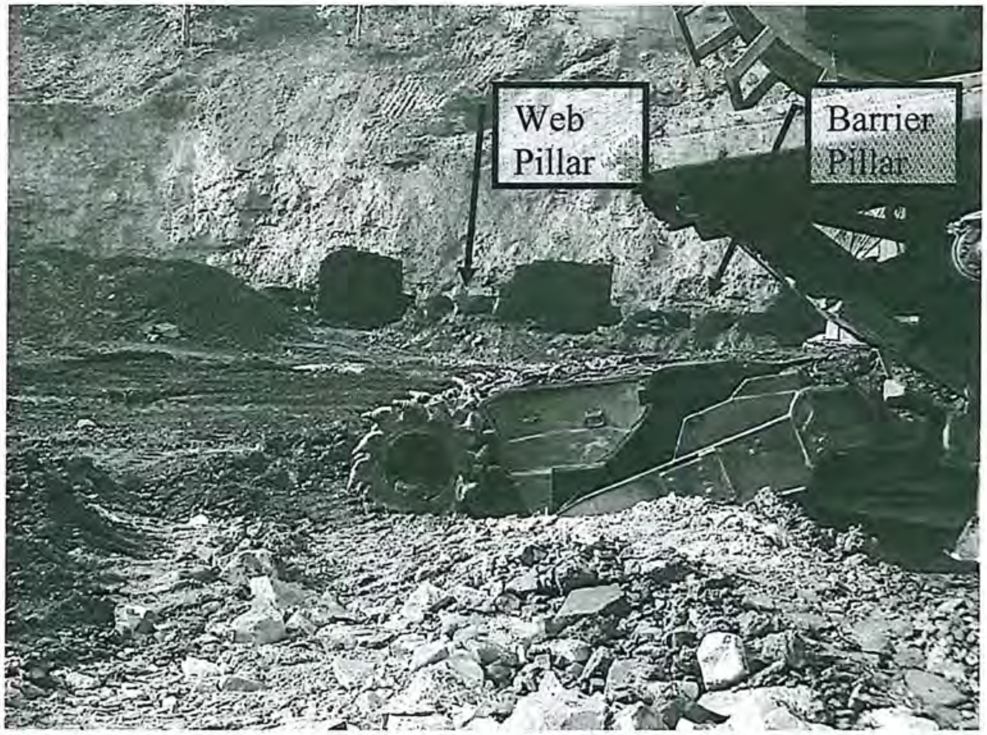


Figure 18. Highwall miner web and barrier pillars with old auger holes.

Table 3. Auger hole geometry and highwall miner web pillar strength.

Auger hole diameter (m)	Auger hole centre-to-centre spacing (m)	Auger web width (m)	Auger web width to hole diameter ratio	Auger % extraction	Highwall miner web pillar strength (MPa)
0.6	1.0	0.4	0.66	60	3.50
0.7	1.0	0.3	0.43	70	2.75
0.8	1.0	0.2	0.25	80	2.00

becomes most problematic when the interburden thickness between seams decreases to less than about one highwall miner hole width (4 m or 12 ft). While firm data on the number of highwall mining operations engaged in such multiple-split mining are not available, anecdotal evidence suggests that 20–40% of highwall mining operations will encounter such mining conditions somewhere on a property.

Close-proximity multiple-split highwall mining appears to have caused several extensive highwall failures of the type that may pose a ground control danger to the working crews. Figure 20 shows one example where a 1.5 m thick (5 ft) lower seam split was mined first followed by the 0.9 m thick (3 ft) upper seam split. A weak, laminated interburden ranging in thickness from 1.2–3 m (4–10 ft) separated the two splits. Catastrophic collapse (or domino failure) of the web pillars occurred that resulted in this extensive highwall failure.

Figure 21 shows a likely failure mechanism that leads to web pillar collapse in closely spaced seams. When web pillars are not stacked, they will load the interburden beam and induce tensile

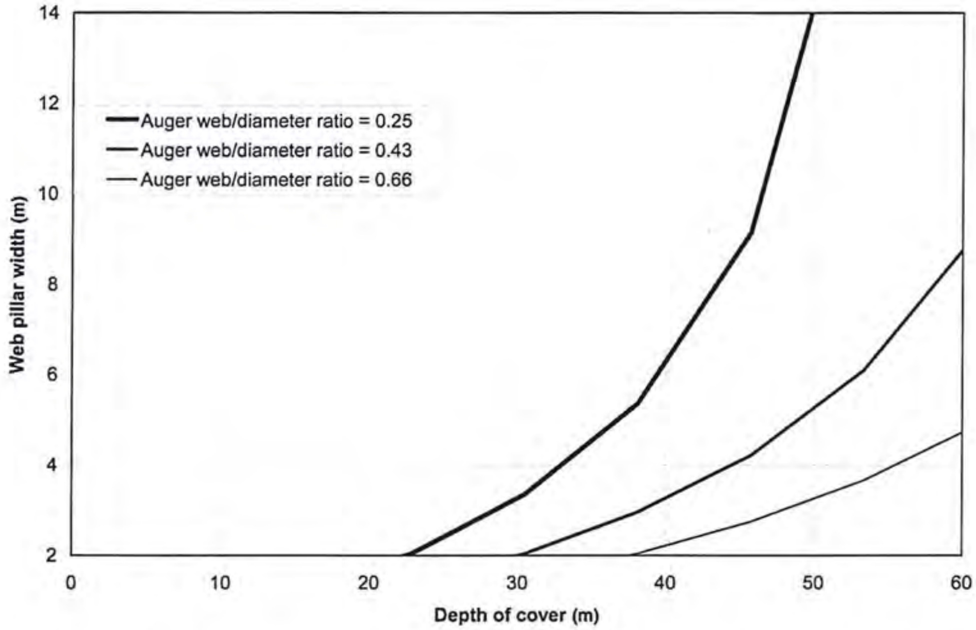


Figure 19. Design chart for web pillars with auger holes of various density.

Figure 20. Highwall collapse in close proximity multiple seam mining area.

failure in its lower outer fibres. Using simple beam theory, Zipf (2005) showed that the maximum allowable web pillar load σ_{PMAX} depends on the tensile strength of the rock σ_{Trock} in the lower

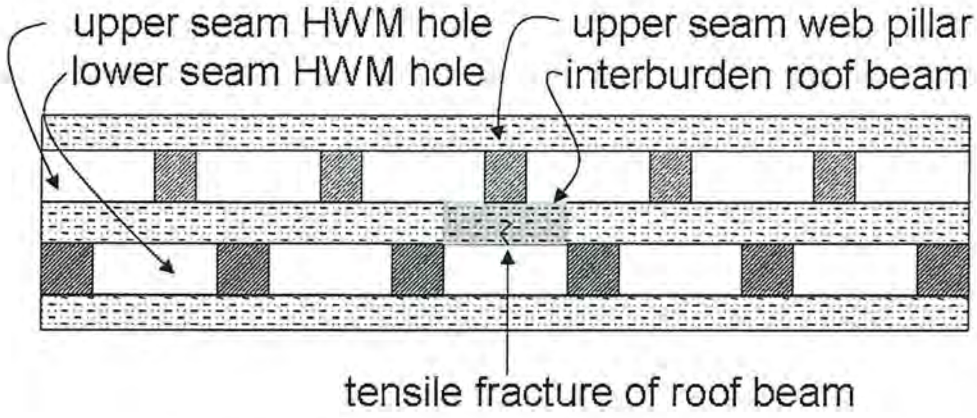


Figure 21. Pillar-beam failure mechanism.

outer fibres of the beam. For a typical geometry as shown in figure 21, the approximate strength of the pillar–beam system is less than the tensile strength of the rock by a factor of 2–4! The compressive strength of a typical highwall mining web pillar is of the order of 8 MPa (1160 psi). The tensile strength of rock may be of the order of 2 MPa (290 psi). According to this simplistic analysis, the strength of a pillar–beam system is of the order of 1 MPa (145 psi), and is therefore much less than the typical web pillar strength. Thus in close-proximity multiple-split mining conditions, strong countermeasures are required to prevent this failure mechanism from occurring and inducing a possible highwall failure.

The obvious solution to prevent this failure mechanism from occurring is to carefully stack upper and lower seam web and barrier pillars. Attaining proper stacking is simple at the start of a hole, but there is no guarantee that stacking will be maintained deep within the holes. Improper stacking appears to have figured prominently in both web pillar collapses and highwall failures shown in figures 10 and 19.

While maintaining proper stacking of web pillars along the entire hole depth is difficult to achieve, maintaining proper stacking of barrier pillars is more practical owing to their greater width. In conjunction with carefully aligned barrier pillars, limiting the number of highwall miner holes to about five will also lessen the possibility of web pillar collapse and highwall failure in these close-proximity multiple-seam highwall mining situations.

8. Highwall mining performance analysis

As part of their safety research effort in highwall mining, Pittsburgh Research Laboratory personnel analysed highwall mining performance data from several highwall mining operations. For planning purposes, most operators develop maps showing the location, orientation and length of their highwall mining holes. Upon completion of mining, the maps are updated to show the actual hole depth mined and the reason for early pull out, if applicable. The analyses conducted herein sought to understand the reasons for early pull out from highwall mining holes in order to avoid trapped miners, improve highwall stability and improve safety.

The company maps covered a three-year period from late 2000 to early 2003, during which time 5289 holes were mined for a total of 780 300 completed metres (2 560 000 ft) of highwall mining hole. Total planned metres was estimated at about 972 900 m (3 192 000 ft); therefore, 192 600 m (632 000 ft) or about 20% of planned hole length was lost due to early pull out.

8.1 ***Hole completion analysis***

This analysis examined the various reasons for early pull out from highwall mining holes. After examining the maps containing the highwall mining performance data, eight categories were created to summarize the hole completion notes for each hole as follows:

1. full depth—no explanation necessary;
2. mechanical/electrical—due to broken hydraulic hose, low oil pressure, an overheated motor, tripped breaker and so forth;

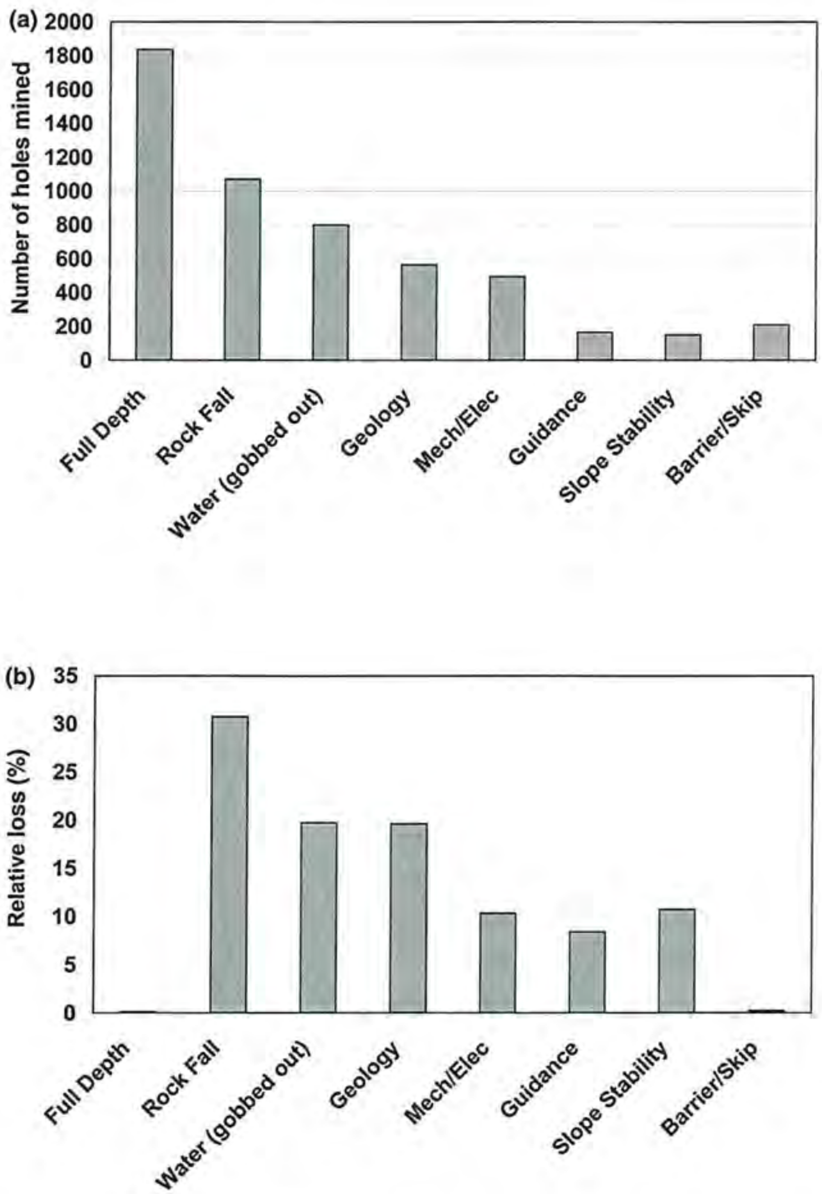


Figure 22. Loss category analysis of 5289 highwall mining holes (a) and relative losses versus loss categories from 972 900 m and 192 600 loss m (b).

3. guidance—due to crossed holes;
4. slope stability—due to a bad highwall;
5. water—due to the hole flooding or severe mud causing the hole to become 'gobbed out';
6. geology—due to a pinching coal seam, a bad roll or hard cutting due to a rock parting;
7. rock fall—due to bad ground or bad ribs;
8. barrier/skip hole—no explanation necessary.

Figure 22(a) shows the number of successfully completed holes (full depth) and the number of holes pulled out of for one of the above reasons. Some findings are:

1. only 35% of holes reached the full depth planned;
2. approximately 20% were short due to rock falls;
3. approximately 15% were short due to water problems;
4. approximately 11% were short because of adverse geology;
5. approximately 10% were short due to mechanical/electrical problems;
6. guidance problems and slope stability accounted for the remaining 9% of shortfalls.

Further analyses estimated the coal losses due to early pull out associated with each of the above loss categories. Figure 22(b) shows that about 31% of the coal losses are due to rock fall, about 20% of the losses were due to water and 'gobbing out' and another 19% are due to adverse geology. Slope stability and mechanical/electrical problems with the highwall miner each accounted for about 11% of the losses, and guidance (crossed holes) caused the remaining 8% of the losses. A hole completion analysis was completed for each property and each seam. Different loss categories became more or less important depending on mining property or coal seam, but generally, rock fall and water ('gobbing out') remained the dominant reasons for early pull out.

8.2 *Stability factor analysis*

For each panel or logical group of highwall mining holes, web pillar thickness was measured and a maximum depth of cover was estimated. Tributary area theory was used to estimate average pillar stress. These pillar stress estimates did not account for the presence of barrier pillars so the computed stress is probably conservative. Pillar strength was computed using the Mark–Bieniawski strength formula for strip pillars assuming an in-situ strength of 6.2 MPa (900 psi) for the coal.

The stability factor for over 3000 individual highwall mining holes was then estimated from the average stability factor for the corresponding panel. About 75% of the stability factors were in the range from 1.3–2.2 and averaged about 1.6 as expected. About 5% of the stability factors were in the 1.0–1.3 range and the remaining 20% were above 2.2. No stability factors were estimated to be below 1.0.

Having a stability factor estimate for each highwall mining hole, an attempt was made to correlate this stability factor to the loss category and some performance measure such as depth of hole achieved or coal losses due to early pull out. The working hypothesis was that a lower design stability factor should result in more coal losses due to geotechnical problems such as rock falls or possibly slope instability.

Four groups of stability factors were considered, namely 1.00–1.30, 1.31–1.60, 1.61–2.00 and more than 2.01. In each of these stability factor groups, the relative losses were evaluated for each loss category. Figure 23 shows the result. The mechanical/electrical, slope stability and water (gobbed out) loss categories showed no discernable dependence on stability factor. Losses due to

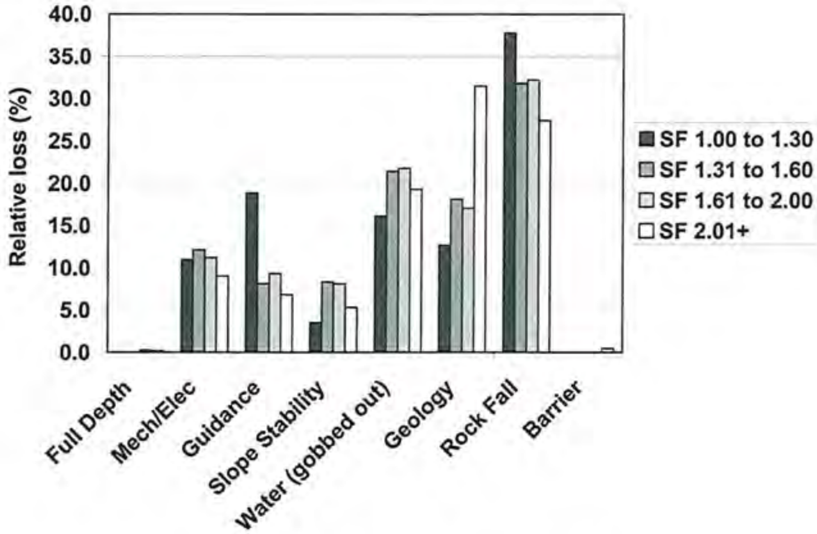


Figure 23. Stability factor analysis.

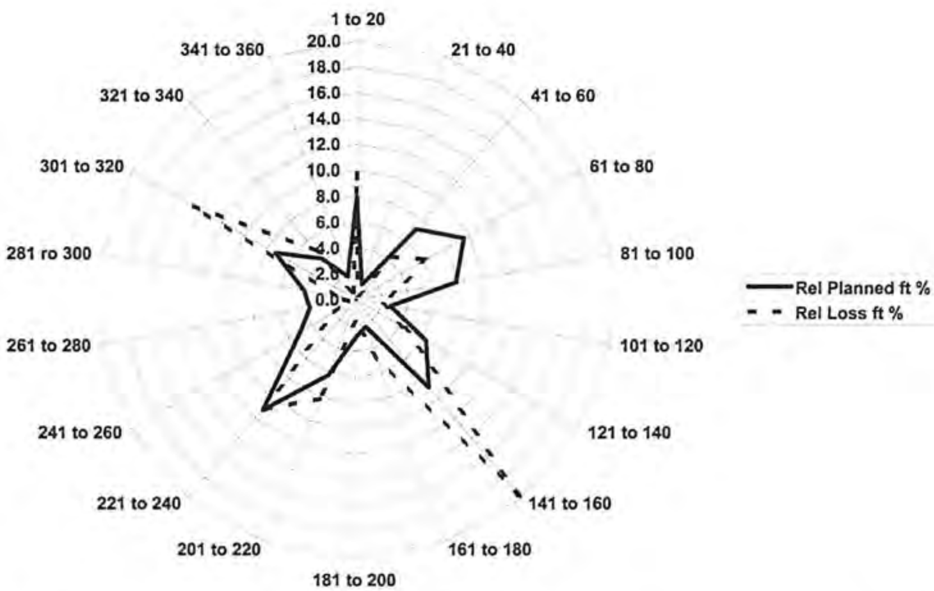


Figure 24. Orientation analysis of planned and lost hole (%) versus orientation for water (gobbed out) failure mode.

guidance problems (crossed-holes) appear high when the stability factor is low. A possible explanation is that low stability factors imply narrower web widths and an increased chance for crossed-holes. In addition, losses due to adverse geology such as rolls and pinching seams appear to increase at higher stability factor. A possible explanation is that at higher stability factor, other causes of loss such as guidance, slope stability and rockfall do indeed decrease and therefore render geology losses more prominent. However, these trends may not be statistically significant.

The rock fall category does show that losses decreased as the stability factor increased; however, it too may not be statistically significant. For stability factors in the range 1.0–1.3, rockfalls were the dominant reason for early pullout from the holes. With stability factors above 1.6, reasons other than rockfalls become the main reason for short holes. The planned stability factor for most of the highwall mining holes was about 1.3 and use of this relatively high stability factor minimizes losses due to rock falls and other geotechnical problems. No statistically significant correlation was found between web pillar stability factor and losses due to rock falls. The primary recommendation from the stability factor analysis is to continue designing web pillars with a minimum stability factor of 1.3.

8.3 *Orientation analysis*

This analysis examined the effect that hole orientation (in other words the direction of mining) had on lost footage and failure mode. The direction of the highwall mining hole had a clear and significant influence on the success rate and reason for failure. Holes mined in a northeasterly or southwesterly direction appear to be more successful than those driven in a northwesterly or southeasterly direction. Figure 24 shows the planned footage (solid line) for each direction as a percentage of the total planned hole length of 972 900 m (3 192 000 ft). Also shown is the lost hole length (dashed line) as a percentage of the total lost of 192 600 m (632 000 ft). When the dashed line is inside the solid line, it indicates lower proportional losses and a more favourable mining direction with greater recovery and fewer problems. Conversely, when the dashed line is outside the solid line it indicates higher proportional losses and a less favourable mining direction. As shown in figure 24 (which considers all holes and all failure modes) a northeasterly or southwesterly mining direction is more favourable than a northwesterly or southeasterly direction. The orientation effect is most likely determined by regional dip. In the central Appalachians, rock strata generally strike northeast–southwest and dip very gently either northwest or southeast.

9. Summary and conclusions

Highwall mining is an important coal mining method in the USA, where upwards of 60 active highwall mining machines may account for approximately 4% of total US coal production. Analysis of MSHA accident data over the 20-year period from 1983–2002 identified nine fatalities associated with auger and highwall mining, and found that ground failures accounted for a third of these fatalities. One fatality caused by ground failure occurred in the last five years of highwall mining. Estimates of the fatality and injury rates for highwall mining suggest it is approximately the same as for surface coal mining and considerably lower than for underground coal mining.

Highwall stability remains a major concern during highwall mining. Geologic structure (hillseams) and pillar stability are the two major factors affecting highwall stability. Operators cannot control the location of hillseams or reliably detect their presence. Planning, inspection, monitoring, good blasting techniques and a lower highwall slope angle are among the available techniques to decrease the risk from highwall failure along hillseams and other geologic structure. Engineering away the safety risk by decreasing the highwall slope angle appears to be the best and possibly the most economic solution to the hazard posed by hillseams.

MSHA requires highwall miner operators to develop and follow a highwall mining ground control plan that usually specifies web and barrier pillar size necessary to maintain highwall stability. This study examined numerous MSHA highwall mining ground control plans and summarized key elements contained therein such as the width, W/H ratio and stability factor of both web and barrier pillars. These data provide useful guidance for judging the viability of a design. In more than 75% of the cases examined, web pillar stability factor exceeded 1.3, and also in 75% of the cases considered, the web pillar width-to-height ratio exceeded 1.0. From the limited data available, barrier pillars were spaced every 5, 10 or 20 holes in 15, 44 and 37% of cases studied. Barrier pillar width appears to exceed 4.6 m in more than half the cases, and barrier pillar width-to-height ratio exceeds 3 in two thirds of the cases.

This study summarizes the essential relations necessary to calculate the applied stress and strength of web and barrier pillars used in highwall mining. These relations are the basis for simple design charts for selecting web and barrier pillar widths. One set of charts provides suggested web pillar width given the overburden depth, mining height and highwall miner hole width. The various charts assume stability factors of 1.3 and 1.6. In addition to web design during the planning phase, these charts allow the user to estimate web pillar stability while in the field. Another set of charts provide suggested barrier pillar width given the overburden depth, mining height and panel width between barrier pillars. These charts neglect the strength of web pillars within the panel and assume a stability factor of 1.0 for the barrier pillar. In checking the suggested web and barrier pillar widths from these charts against the ARMPS program, the charts always provide a conservative (high) suggestion for pillar width and a low estimate for the stability factor of a web and barrier pillar system.

This study also considered two special design cases, namely highwall web pillars that contain old auger holes and close-proximity multiple-seam highwall mining. The strength of a highwall mining web pillar containing auger holes is 25% to as little as 15% of the solid web pillar strength, and it depends on the ratio of auger web width to auger hole diameter. A design chart is presented for estimating highwall mining web pillar width when auger holes are present.

Close-proximity multiple-split highwall mining appears to have caused several extensive highwall failures that may have posed a ground control danger to the working crews. The likely mechanism for these multiple-seam web pillar collapses and the induced highwall failures arises from improper stacking of the web pillars in conjunction with a thin interburden (less than one highwall miner hole width) between seams. Careful stacking of web pillars, careful stacking of barrier pillars and decreasing the number of highwall miner holes between barrier pillars will all help prevent this failure mechanism from occurring. It may be difficult to maintain proper stacking of web pillars; however, due to their greater width, maintaining proper stacking of barrier pillars is more practical. Limiting the number of highwall miner holes to about five also decreases the possibility of serious web pillar collapse due to adverse stacking and subsequent highwall failure.

Finally, this study examined performance of highwall mining by studying field records from 5289 highwall mining holes with a total completed hole length of 780 300 m (2 560 000 ft) out of 972 900 m (3 192 000 ft) planned. Average loss was almost 20% of planned hole length and only 35% of the holes reached full depth. Rock falls in the hole, water and adverse geology accounted for 70% of the losses, while mechanical/electrical problems, guidance and bad highwall slopes accounted for the remainder.

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