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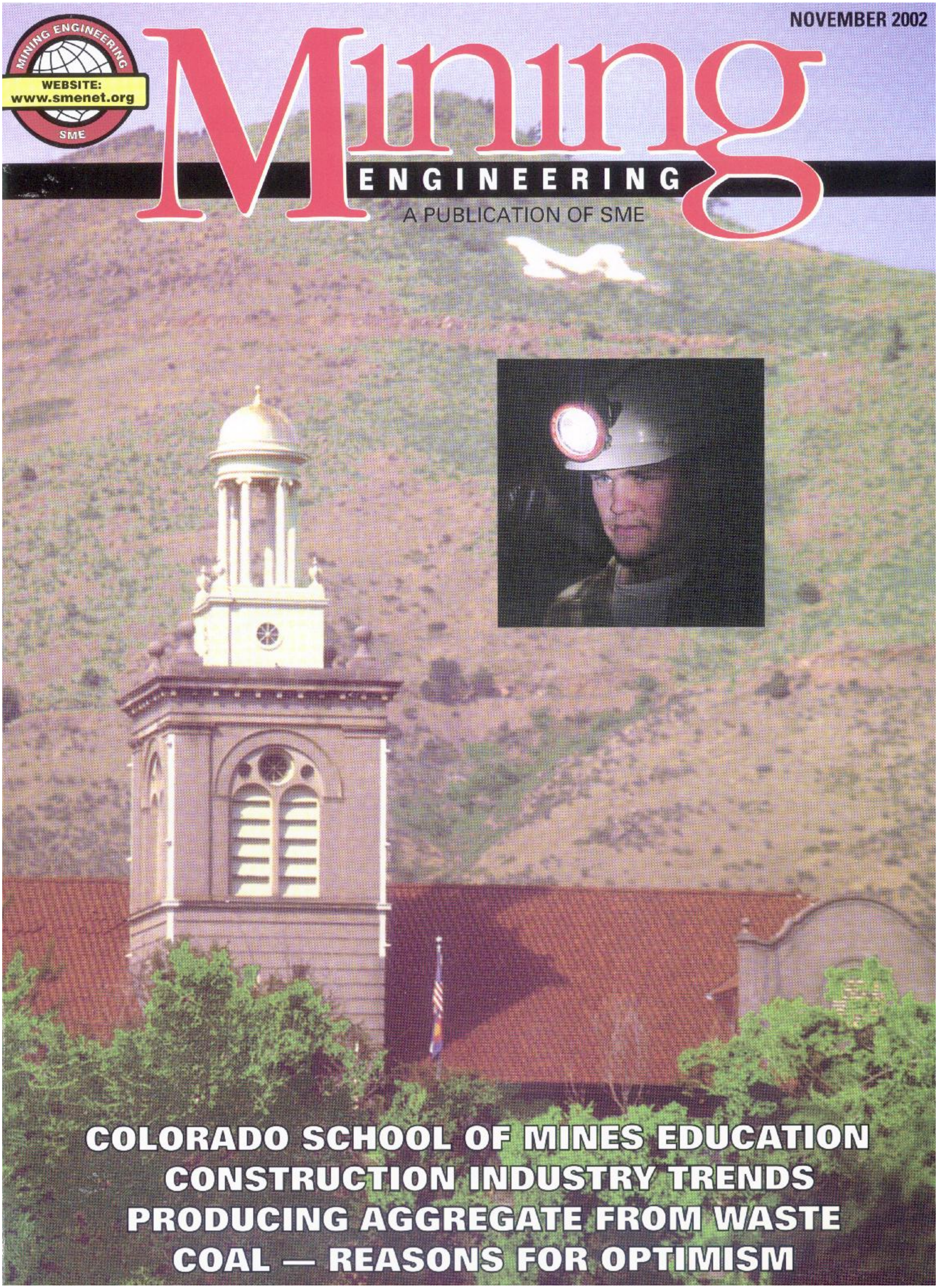


COLORADO SCHOOL OF MINES EDUCATION
CONSTRUCTION INDUSTRY TRENDS
PRODUCING AGGREGATE FROM WASTE
COAL — REASONS FOR OPTIMISM

Prefailure pillar yielding

J.F.T. AGAPITO AND R.R. GOODRICH

J.F.T. Agapito, member SME, and **R.R. Goodrich** are president and associate, respectively, with Agapito Associates Inc., Grand Junction, CO. Preprint number 01-003, presented at the SME Annual Meeting, Feb. 26-28, 2001, Denver, CO. Revised manuscript received and accepted for publication January 2002. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications Dept. prior to Feb. 28, 2003.

Introduction

Yield pillars have been used in mining for many years to reduce stresses near mine openings, to allow higher resource recovery at depth and to minimize surface subsidence effects. Their application has led to successful and unsuccessful results. In some mines, yield pillars were abandoned because of poor ground conditions. It became obvious that yield pillars needed the right combination of strength and stiffness in the materials composing the overburden, roof, pillar and floor for successful results. When this was present, considerable safety and economic benefits were attained.

Significant stress control was thought possible only after the pillars reached their peak strength (failure) and considerable yielding had occurred. However, experience has shown that prefailure yielding was beneficial for reducing stresses with narrow mining widths, such as development entries. Pillar stiffness was reduced by reducing the pillar widths. And the headings were advanced close together for mutual stress relief. This was achieved by trial and error. The amount of stress reduction was unknown, but the results often showed improved ground conditions.

In soft strata, prefailure yielding is often present but unintentional in the design. Experienced miners recognize that yielding and arching is "probably" present, with some pillar loading transferred to barriers.

This paper presents quantitative data on prefailure yielding based on stress determinations, showing that significant stress reduction can be achieved without compromising long-term stability. A recommendation is made for incorporating planned yielding in mine design.

The concept

It is unknown when the yield pillar concept was first recognized, but it was probably more than 100 years ago. With increased usage of regular pillar patterns (board-and-pillar mining), miners began to observe that ground conditions sometimes improved when pillars yielded and fractured slightly. Eventually, it became apparent that the stresses could be decreased locally, with some of the overburden load transferred to large pillars or unmined ground (abutments) by pillar yielding.

Overburden stress transfer was visualized to occur through pressure arching onto side abutments. It was deduced that the yield pillars support only the overburden weight below the arch. The wider the arch, the higher its height and the higher the abutment loading. Arching occurs as long as the mining width does not exceed a critical dimension — the critical pillar arch width. If this is exceeded, the pressure arch breaks and the yield pillars are subjected to full overburden loading, potentially leading to total pillar collapse and extensive surface subsidence.

The need for limiting surface subsidence played an important role in the development of yield pillar systems where narrow, high-extraction areas (panels) separated by barrier pillars were used. Figure 1 shows a cross section of a typical panel with a simplified depiction of a pressure arch. Obviously, arching is more complicated

Abstract

Yield pillars have been used for many years to help reduce stresses near mine openings and improve roof and floor stability. A yield pillar is often defined as a pillar that fails but retains residual strength. Stress transfer occurs through the roof and floor after the peak strength of the pillar is reached. High stresses are transferred from around the openings onto abutments that can be barrier pillars or unmined ground. This mechanism, often referred to as pressure arching, is possible as long as the width of yield pillar mining (panel width) is less than the critical width above which stresses cannot be carried by the overburden. Significant stress transfer also can occur due to small amounts of pillar and/or floor yielding before the peak strength is reached. This is accomplished in a quasi-elastic manner with little or no visible roof and pillar fracturing or floor heave. Long-term stability may be achieved when stresses and mechanical properties are favorable to prefailure yielding. This paper gives practical examples where improvements in stability and resource recovery were achieved with this mechanism. Yielding was assessed by comparing measured and calculated vertical pillar stresses. Results indicated that calculated stresses in the pillars were 25% to 40% higher than the measured stresses, demonstrating significant arching load transfer to the abutments. Prefailure yielding is probably often present but unintentional in both development and production areas. Better recognition and use of this mechanism should lead to design improvements, as mines become deeper.

than shown in Fig. 1, with multiple arches forming an intricate three-dimensional pattern over the openings. Yielding occurs not only in the pillars, but also in the roof and floor.

FIGURE 1

Pressure arch.

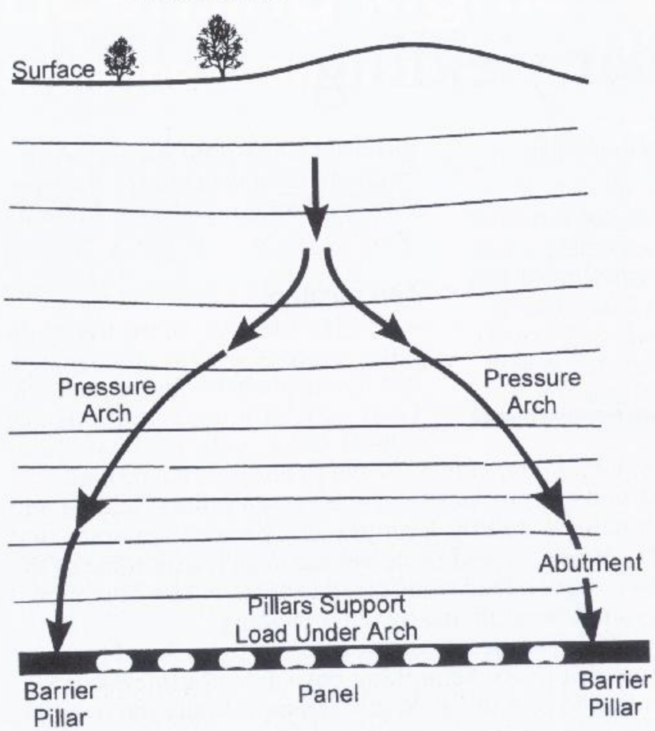
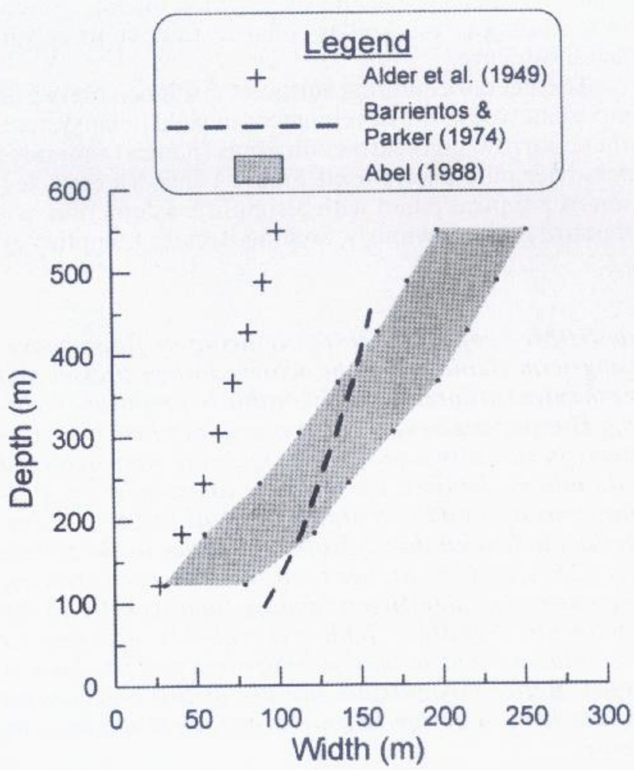


FIGURE 2

Relation between critical width and depth.



Pressure arch widths

Experience has shown that the pressure arch width increases with depth. There are great differences in reported critical widths. This is probably due to differences in geology and to differences in the way the observations were made and interpreted.

Figure 2 shows critical widths for different depths from three sources. Curve 1 (Alder et al., 1949) was based on observations from coal mines in the north of England, and the data were presented as "very conservative" by the authors. Curve 2 (Barrientos and Parker, 1974) critical widths were obtained from a copper mine and were derived from a differentiation between collapsed pillar areas that did and did not result in surface subsidence. Curve 3 (Abel, 1988) was based on 55 cases from mines in sedimentary strata (mostly coal mines, two salt mines and one trona mine). The yield pillars in the center of a panel have the longest transfer distance to the side barrier pillars and carry the highest load within the arch. The critical width equals two load-transfer distances.

Longer load-transfer distances than those shown in Curve 3 (Fig. 2) have been measured in western mines. For example, a load-transfer distance of 230 m (750 ft) was measured at a depth of 610 m (2,000 ft) (Goodrich et al., 1999). This indicated the possibility of a pressure arch width of 457 m (1,500 ft). In another example, panel widths of 240 m (787 ft) are being used successfully with yield pillars at depths of 250 m (820 ft) (Agapito et al., 2000). This experience indicates that loading may be transmitted by parabolic pressure arches (Abel 1988) and also by thick beam or flat arch mechanisms.

Three examples of prefailure yielding

It is often believed that significant stress transfer is possible only after the peak strength is reached and the pillars fracture into a post-failure stage. However, large amounts of stress transfer also occur before the peak strength is reached. These prefailure yield pillars can provide good long-term stability.

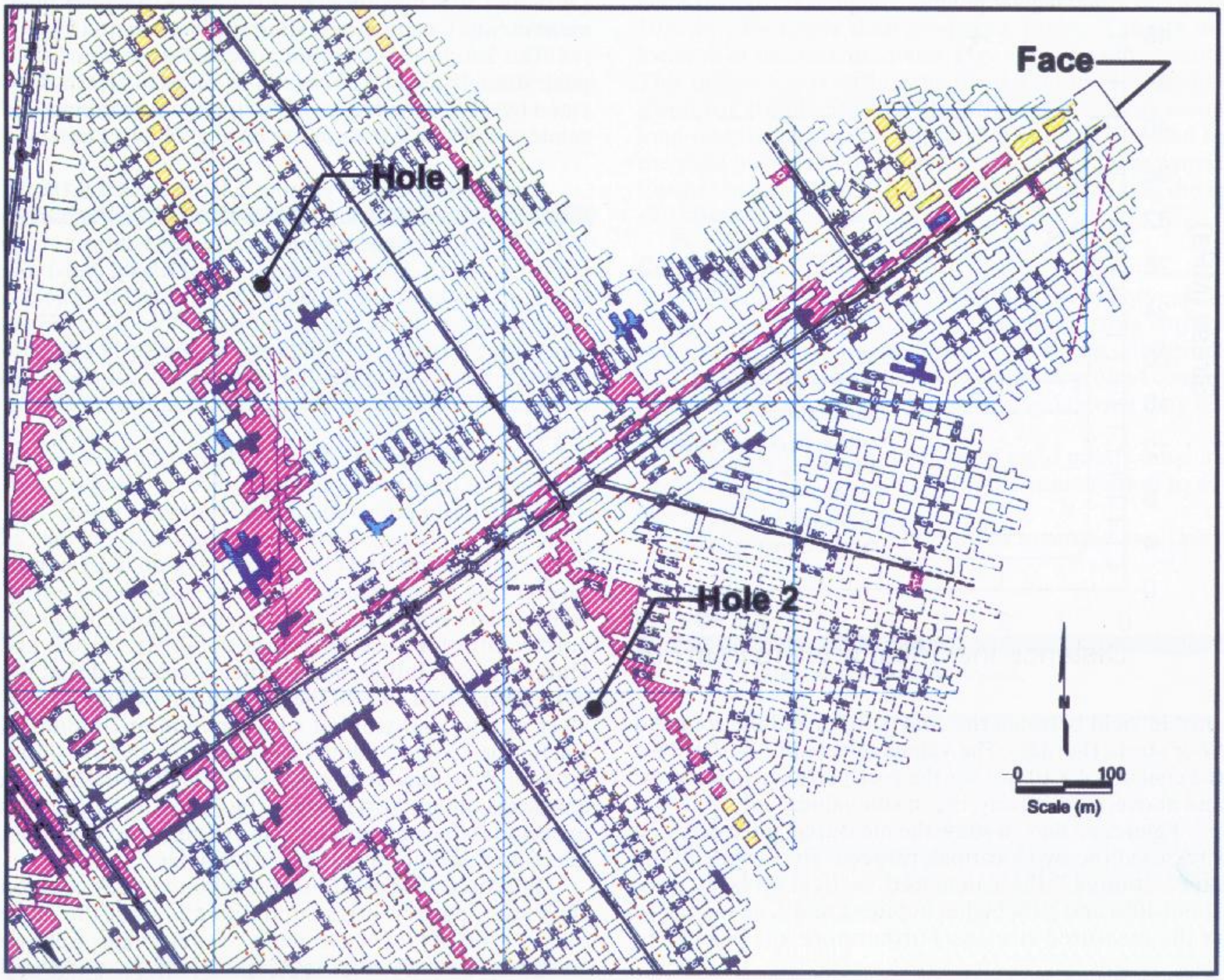
Copper mine. In the White Pine Mine, located in Michigan's Upper Peninsula, productivity and resource recovery limitations, due to increased depth and high horizontal stresses, led to the use of postfailure yield pillars (Barrientos and Parker, 1974). Yield pillar mining was initially successful. Optimistic forecasts were made for improved ground control and productivity at depth, mostly in areas where subsidence had to be minimized (Pothini et al., 1976). However, the method was abandoned for production areas because of rock fall problems (McGunegle, 1992).

Pillar yielding for development was more successful. Pillar widths were reduced in mains to allow small amounts of yielding only and mutual stress relief between advancing entries. Improved ground conditions were obtained without increased pillar fracturing, especially in the central entries, as compared to developments using wide pillars. This prefailure yielding was introduced successfully to production areas in the mid-1980s.

As the mine depth increased, small square and rectangular pillars were used for inducing small amounts of yield. Figure 3 shows the location of two panels at a depth of 625 m (2,050 ft), with the same extraction ratio

FIGURE 3

Plan view of development and production panels.



where pillar stress determinations were made. The measurement results show remarkably close vertical-stress profiles in both square and rectangular pillars (Fig. 4).

The measured average vertical stresses were about 30 MPa (4,350 psi), as compared to 41 MPa (5,950 psi) calculated by the tributary area method, indicating 27% less than overburden loading. The overcoring measurements were made about five years after mining. Good stability was shown at this time by roof-to-floor extensometer measurements. Appreciable convergence had occurred after mining, but this movement gradually decreased with time. Little or no convergence (yielding) was being measured when the stress measurements were made.

After the overcoring measurements were made, three vibrating wire stress meters were installed in the rectangular pillar. One 2-m- (6-ft-) wide, 15-m- (50-ft-) long cut was mined from the pillars in this panel, resulting in the increase in stresses shown in Fig. 4. The estimated pillar load increased from 30 to 42 MPa (4,350 to 6,100 psi), with no visible indication of pillar failure. The pillars were still stable when the mine was closed, three years after the overcoring measurements.

The room-and-pillar design at White Pine evolved by trail and error. By the time the mine was closed, mining was being conducted at depths thought unlikely 30 years earlier. The use of small amounts of pillar yielding was one of the factors in helping ground control and in extending the mine life.

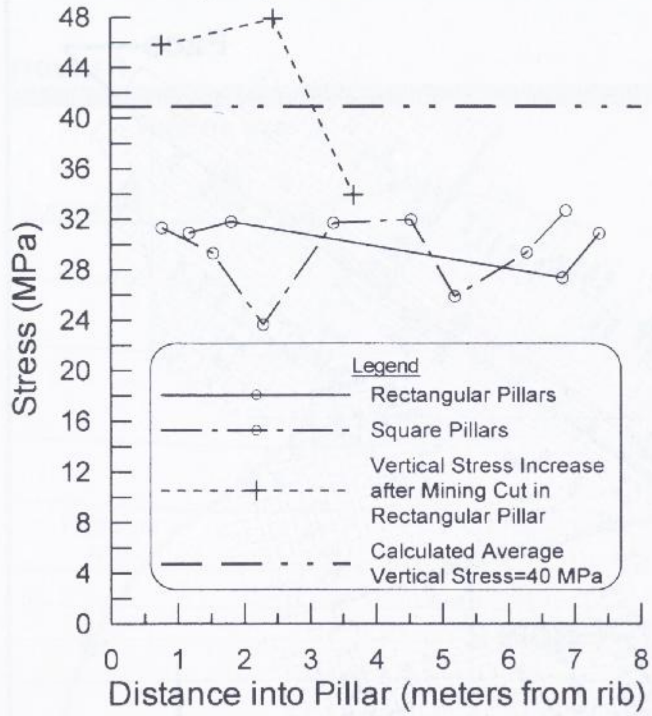
Coal mine. The Deer Creek Mine is operated by Energy West Mining Co. It is located in the Wasatch Plateau about 42 km (26 miles) southwest of Price, UT. Longwall mining has been conducted successfully at depths of more than 610 m (2,000 ft). The use of a two-entry yield pillar system was a major factor in reducing significant bump problems (Agapito et al., 1988).

As part of a stability evaluation, overcoring measurements were made in two locations of a gateroad prior to longwall mining (Fig. 5). The objective was to determine pillar loading before abutment loading from the longwall.

The vertical stresses were obtained from inclined holes drilled in the strata above the 7.6-m- (25-ft-) wide yield pillars. At the same time, the stresses were calculated by using a quasi-three-dimensional code. The calculated vertical stresses were "minimized" by selecting elastic properties (moduli) that accentuated the differ-

FIGURE 4

Vertical stresses in square and rectangular pillars.



ence in yield between the coal (softer) and the roof and floor strata (harder). The values selected (2 ¥ 10^5 psi for the coal and 4 ¥ 10^6 psi for the rock) probably are below and above, respectively, the in situ values.

Figures 6a and 6b show the measured and calculated stresses at the two locations, respectively. In spite of the input "tuning," the calculated vertical stresses were about 40% and 30% higher at Sites 1 and 2, as compared to the measured stresses. Furthermore, the calculated vertical premining stresses, simply calculated from the depth and overburden density, are also higher than the measured stresses. The difference between the two sites (40% and 30%) is probably due in part to higher pillar yield in Site 1, caused by a shorter pillar length (Fig. 5).

The 7.6-m- (25-ft-) wide yield pillars reached their peak strength slightly ahead of the longwall face, as indicated by a typical increase in fracturing and spalling, and remained in stable postfailure during longwall mining.

Trona mine. OCI Wyoming, LP operates the Big Island Mine, located 40 km (25 miles) northwest of Green River, WY. Continuous miners are used to extract trona from two 3- to 3.5-m-thick (10- to 11.5-ft) flat-lying seams at depths of 250 to 330 m (820 to 1,082 ft). The distance between the seams is approximately 10 m (33 ft). The application of yield pillars is particularly advantageous in this room-and-pillar mine because the stresses transmitted from the upper to lower seam can be minimized.

The development of the design was based on test mining. The major design phases were as follows:

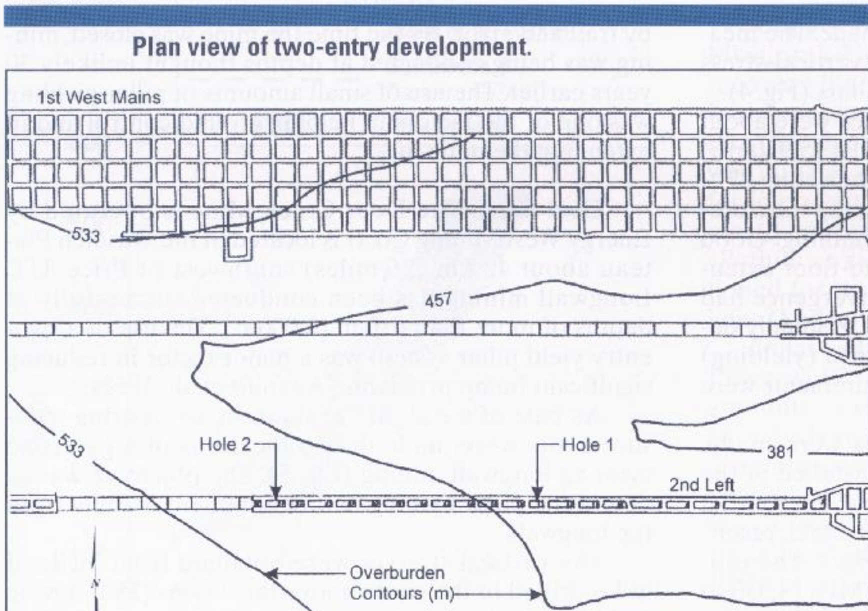
Sizing yield pillars and entry widths: Sizing was obtained by gradual reduction of pillars and increase of entry spans in small test block areas within large panels. Overcoring measurements helped establish the size at which pillars yielded and convergence measurements the entry widths for good long-term stability (Agapito and Hunter, 1989). Initial measurements indicated that the pillars supported 75% of the overburden loading 40 days after mining and yielded with a minimum amount of fracturing. Little reliability was placed in the use of pillar-strength formulae because of difficulties in selecting constants and material properties. Also, the floor was expected to be a major factor in yielding, and this is not taken into account by the pillar formulae.

Selection of dimensions and test mining: A chevron (fishbone) pattern was adopted to allow for the more efficient use of large continuous miners. Panels were on average 240-m (787-ft) wide and 800- to 1,600-m (2,625- to 5,250-ft) long, separated by 20-m- (66-ft-) wide barrier pillars. Yield pillars were laid out in a chevron pattern, 6.5- to 8-m (21- to 26-ft) wide, separated by 9-m- (29-ft-) wide rooms and 4.5-m- (15-ft-) wide crosscuts (Fig. 7). A full-scale test panel was mined without major ground problems.

Evaluation of long-term stability: Good long-term stability is needed to minimize subsidence potential over a large portion of the mine, which lies under the Green River. Long-term stability was evaluated by determining time effects on stress by computer modeling. Results indicated good long-term stability (Agapito et al., 2000). Figure 8 shows the average vertical-stress changes with time for two pillars and the barrier pillar shown in Fig. 7. Good long-term stability is shown by a decreasing rate

FIGURE 5

Plan view of two-entry development.



of stress, which becomes very small after 10 years. The convergence rates follow the same trend. Yielding and load transfer can be visualized as the stresses decrease in the panel pillars and increase in the barrier.

Adoption of design and verification: The chevron pattern for single-seam mining was extended to other parts of the mine. During the last 10 years, about 23 panels have been mined with good stability in both seams. Two-seam mining has not yet been done, and the design is presently being evaluated. Stresses predicted by modeling were checked by overcoring measurements seven years after mining. Results indicated that pillar stresses were 10% to 20% higher, and barrier pillar stresses were 10% to 15% lower than predicted. Figure 7 shows the location of the measurements. Figure 8 shows the results. This difference is within the design limits. The earlier trend for stabilization of the stresses indicates lower long-term deformations, but higher stresses retained by the yield pillars will be transmitted to lower seam panels. Further measurements will be made for obtaining the in situ stress-time curve.

FIGURE 6A

Vertical stresses in yield pillars (Hole 1).

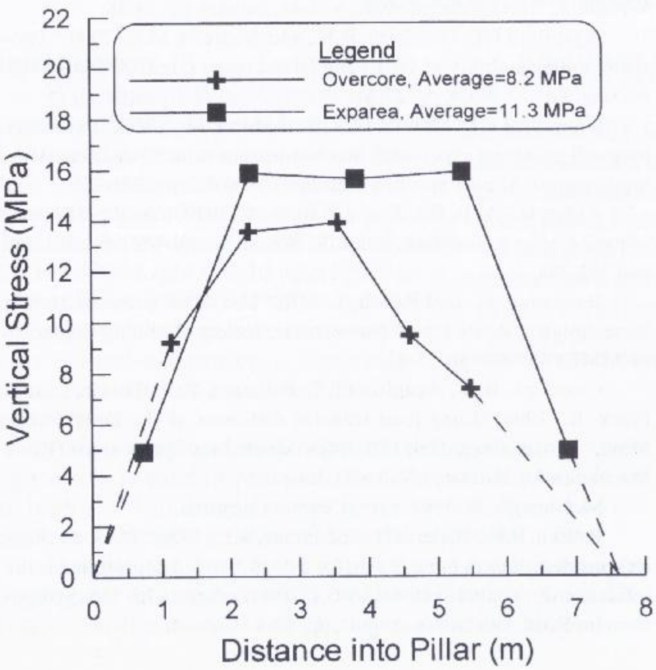
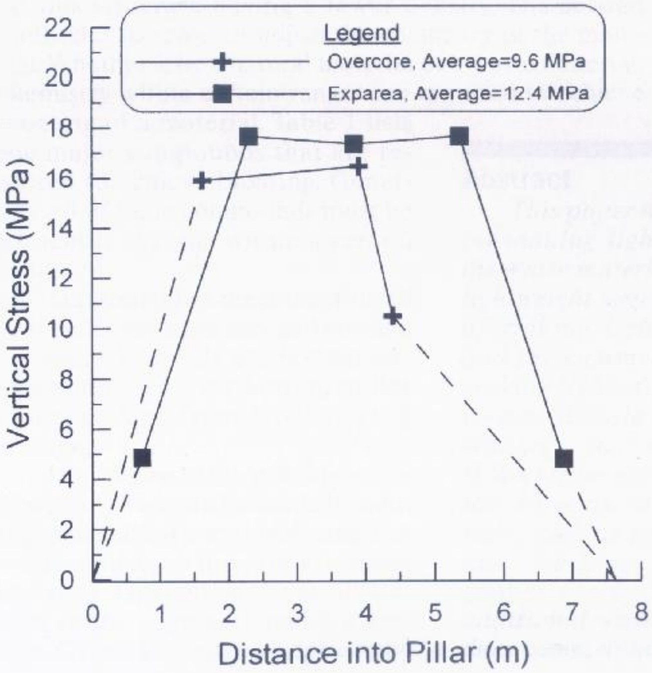


FIGURE 6B

Vertical stresses in yield pillars (Hole 2).



Conclusions

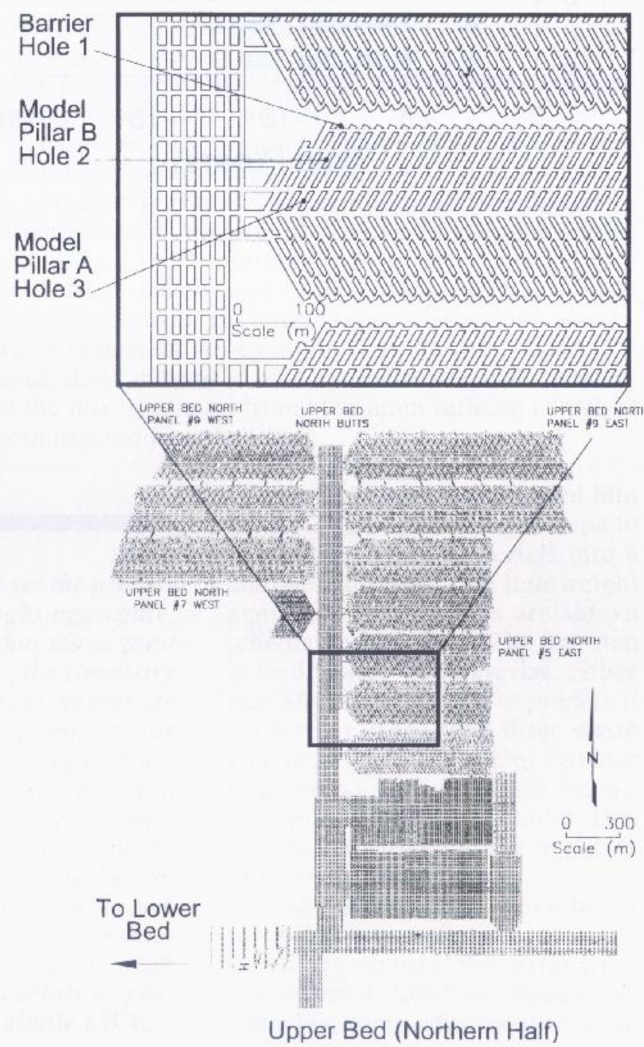
Yield pillars have been recognized for many years as effective for stress control and for minimizing surface subsidence. However, geologic and mining conditions must be favorable for success. Otherwise, ground control problems leading to large roof falls and caving may occur.

The design and application of yield pillars must include test mining and long-term instrumentation to access yielding and stability.

Although a yield pillar is often regarded as a failed

FIGURE 7

Chevron yield-pillar layout.

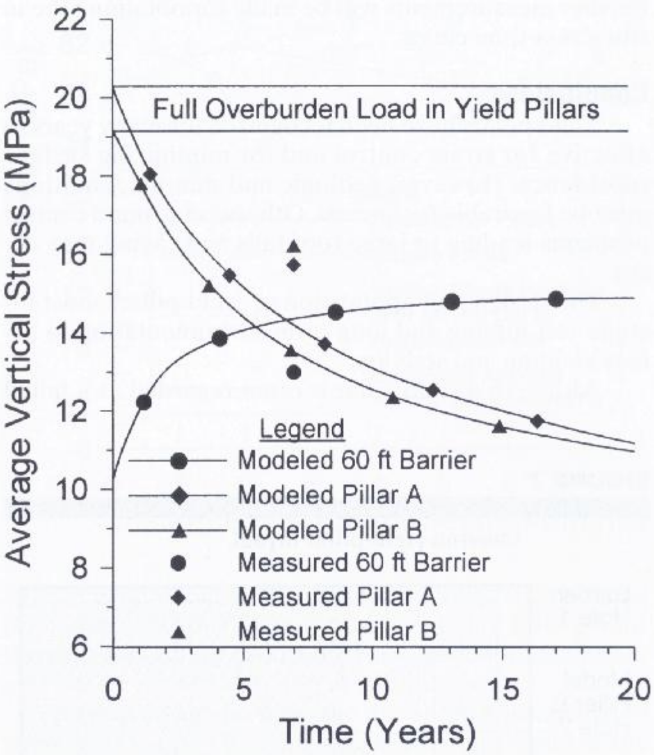


pillar, significant stress reduction and long-term stability can be achieved also by prefailure yielding before the pillar reaches its peak strength. Three examples are described where pillar loads 25% to 40% less than the overburden, without major failure or long-term stability problems, were achieved.

Prefailure yielding is sometimes known to be present, but is seldom included in the design. The amount of stress reduction effected is often unknown, as are the full benefits that may be realized. A better understanding and recognition of this mechanism should lead to improved mine design. ■

FIGURE 8

Comparison of modeled and measured stresses.



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