

7th INTERNATIONAL CONFERENCE ON GROUND CONTROL IN MINING

INTEGRITY FACTOR APPROACH TO ASSESS THE STABILITY OF ROOM-AND-PILLAR MINES

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ABSTRACT

The integrity factor approach was developed by the Bureau of Mines to assess the stability of mine pillars and has been applied primarily to longwall chain pillars. Recently, this approach was applied to a room-and-pillar mine in the Illinois Coal Basin. A special configuration of hydraulic borehole pressure cells was installed in a pillar to determine the in situ strength-and-stress relationship of the coal pillar and to verify the applicability of the integrity factor approach. Results indicate that the integrity factor approach is applicable to the assessment of pillar stability and may be a realistic and effective approach for room-and-pillar mine design.

INTEGRITY FACTOR

The integrity factor approach (1, 2, 3) was developed to overcome the deficiencies of existing conventional pillar design methods. Most conventional design methods are based on the relationships between pillar size or shape and compressive strength, derived from unconfined compression tests on small samples (4). Wilson (5, 6, 7) developed an approach to pillar design based on the concept of stress balance: "Any rise in stress in rib sides and pillars must be offset by an equivalent stress reduction across roadways and other areas of extraction." With this approach, however, difficulties still remain in determining the boundaries between yielded zones and intact core zones within the pillar. The conventional methods use hypothetical stresses, estimated from tributary area or stress balance concepts, instead of measured stresses. In addition, most methods do not consider the time element

and are inadequate for evaluating pillar stability as the mine is developed.

The integrity factor approach relies on field measurements to determine the in situ stresses in a pillar and the load capacity or strength of the pillar. Stresses are determined using encapsulated borehole pressure cells (BPC's), according to the techniques developed by the Bureau of Mines (8). Two cells, one oriented vertically and the other oriented horizontally, are required to determine the vertical and horizontal stresses at a point in the pillar. In addition, a response factor is required to relate cell pressure to ground stress. The response factor is typically obtained by installing a cylindrical pressure cell (CPC) adjacent to the two BPC's. The pair of BPC's (and the CPC, if present) constitute one measurement point. Figure 1 shows the location of the measurement points that were used in this case study to evaluate pillar stability.

The coal strength, or load capacity, at each measurement point is estimated from the results of laboratory triaxial strength tests of core samples taken from the pillar. The average failure curve obtained from a number of samples is used to estimate the compressive strength of the coal for a confining pressure equal to the horizontal stress at the measurement point. At present, the in situ strength at the measurement point is assumed equal to the value obtained from the laboratory curve. However, to compensate for the effects of scale, the use of a reduction factor may be appropriate.

Previous analyses, using the integrity factor approach, have dealt with longwall chain pillars in which the

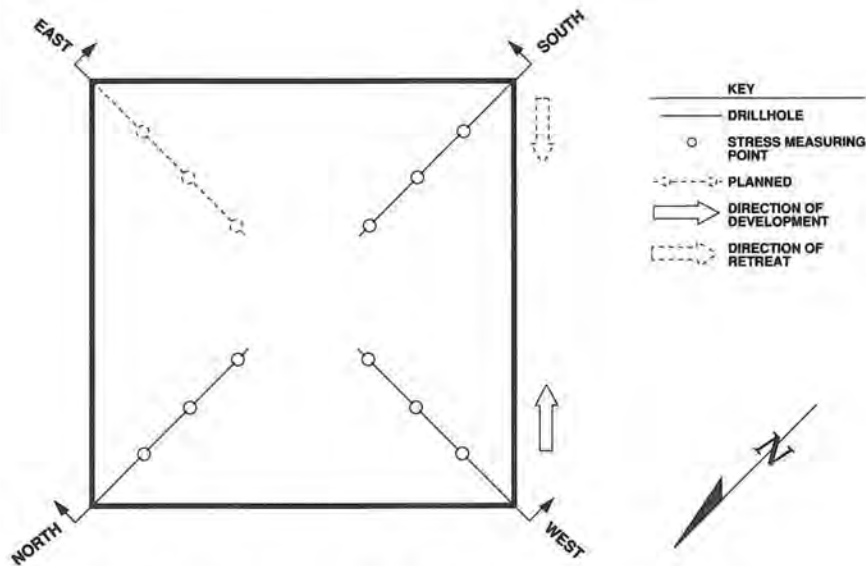


Figure 1. Location of measurement points.

instruments were installed to analyze a vertical slice or plane section through the pillar. The area under the strength distribution curve is the integrated total strength, and the area under the vertical stress distribution curve is the integrated total load. The integrity factor is defined as the ratio of integrated total strength to integrated total load. Pillar failure is expected when the integrity factor becomes less than one.

For a pillar in a room-and-pillar section, the measurement points are distributed throughout the pillar and a different analysis procedure is required. At each measurement point, an individual integrity factor is calculated as the ratio of strength to vertical stress at the measurement point. The distribution of strength, stress, or integrity factor has the form of a three-dimensional surface over the pillar. For each distribution, the ratio of the volume under the distribution surface to the pillar area represents a weighted average of the distribution of strength, stress, or integrity factor. The overall integrity factor, IF, is the ratio of the weighted average of the strength distribution, WS, to the weighted average of the vertical stress distribution, WL.

FIELD INVESTIGATION

A special configuration of BPC's was installed in a room-and-pillar mine in the Illinois Coal Basin as part of a Bureau of Mines research project investigating the stability of coal mine intersections (9). The instrumented

pillar was approximately 18 m square and 2.4 m high and located in the central area of a production panel. The roof and floor at the test site were massive shale, and the overburden thickness was 290 m. Figure 2 shows the installed location of all cells used to determine the integrity factor. The vertically and horizontally oriented BPC's were installed at equal depths but in

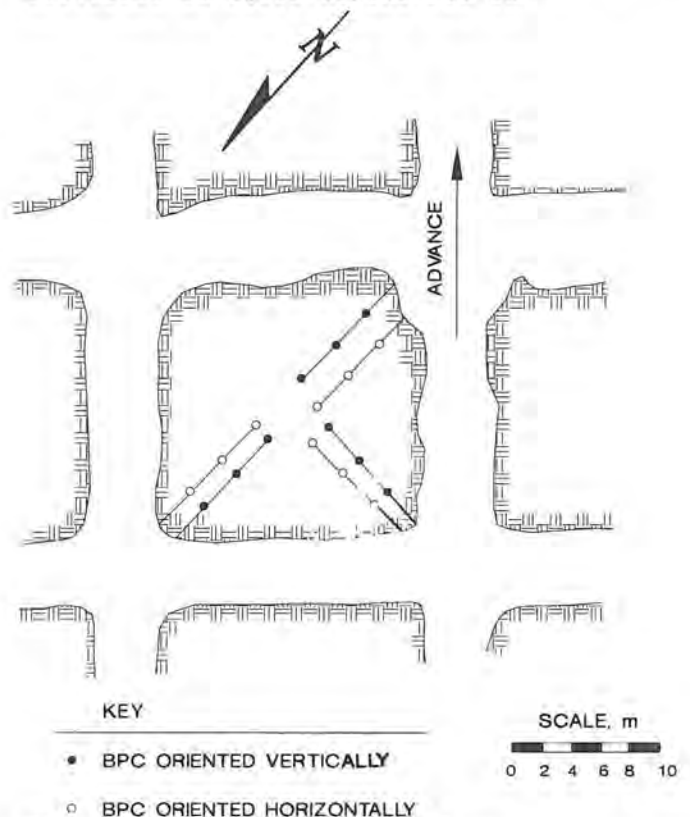


Figure 2. Instrumentation layout.

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separate parallel boreholes along the diagonal lines extending from three pillar corners. The fourth corner had not been developed at the time of installation and could not be instrumented. Each adjacent pair of BPC's, one horizontal and one vertical, corresponds to the measurement points in figure 1. The vertical stresses at the missing measurement points in the fourth pillar corner were approximated by averaging the calculated stresses of corresponding points at the other corners. However, the strengths at the missing points were approximated as the equivalent triaxial strength of laboratory specimens having a confining pressure equal to the average of the horizontal stresses at the other corners. The individual integrity factors at the missing point and all weighted averages were derived using the approximated stresses and strengths. Use of this approximation procedure is intended to better illustrate the application of the integrity factor approach. For actual design purposes, such approximations should not be used without careful consideration of their effects on subsequent calculations.

The instruments were installed during the advance phase of panel development over a two-week period when all mining activity at the test area was suspended (9). Pressure-cell data were monitored continuously throughout the remainder of panel development until retreat operations reached the test area.

During the life of the pillar, the following distinct development stages were observed:

- Stage I - Initial Development
- Stage II - Intersection Development
- Stage III - Long-term Development
- Stage IV - Nearby Caving
- Stage V - Pillar Extraction

The above stages represent periods where the pressure data exhibited distinctive characteristics or trends. The sequence of mining which corresponds to the five development stages is shown in Figure 3. Representative data were selected for each development stage and were used to calculate pillar strengths, vertical stresses, and integrity factors. The procedures followed in determining these parameters are discussed below.

DATA ANALYSIS

Vertical and horizontal stresses at each measurement point were calculated from the BPC pressure data using a response factor of 1.0, a typical value for coal (8). Triaxial compressive strength tests were conducted on coal samples obtained at the mine to determine an average failure curve. Figure 4 shows the results of the laboratory tests. The length-to-diameter ratio of the sample specimens was 2:1 (10.8 cm to 5.4 cm); however, the compressive strengths were normalized to correspond to a 1:1 ratio. This ratio corresponds more closely to the conditions experienced by a

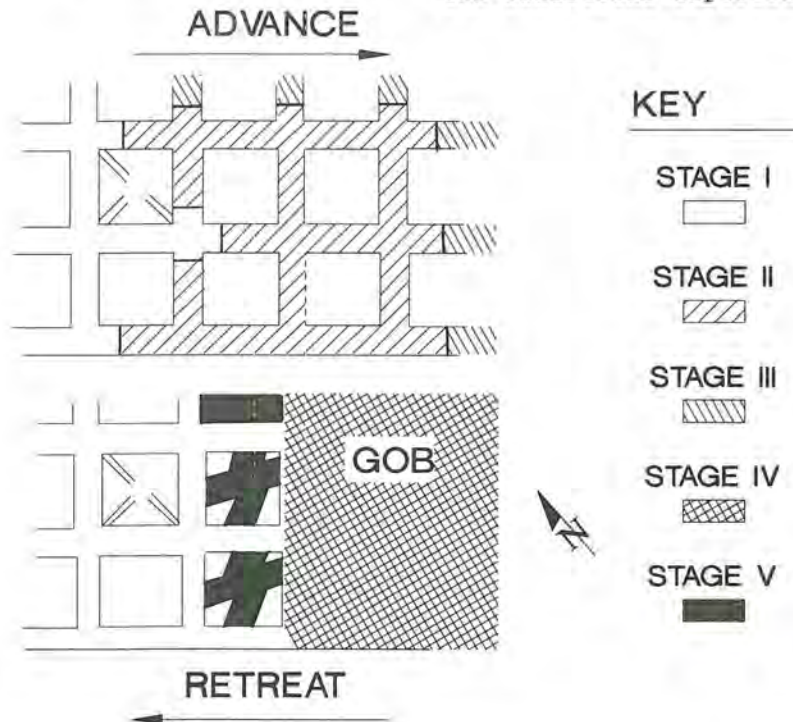


Figure 3. Sequence of mining for each development stage.

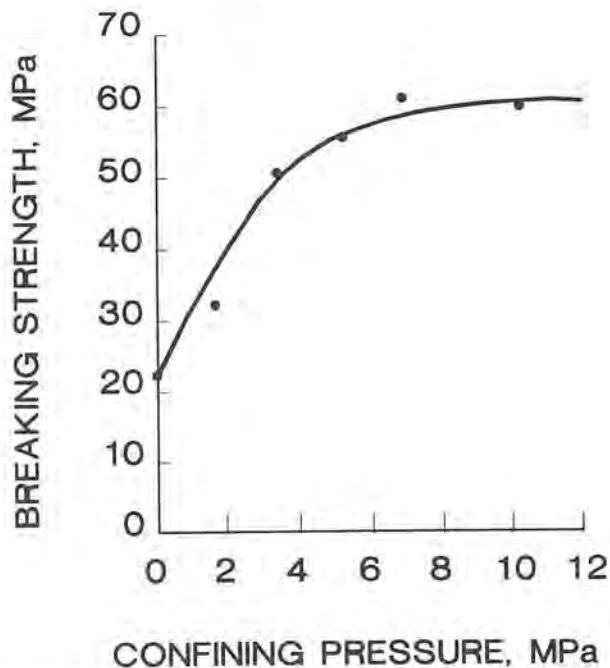


Figure 4. Laboratory triaxial compressive strength of coal.

representative column of coal, approximately 3.0 m in diameter by 2.4 m high, surrounding each measurement point. Each point on the failure curve corresponds to the mean value of the normalized strengths obtained from two to five tests at each confining pressure. The coal strength at each measurement point was estimated to be equal to the breaking strength specified by the failure curve at a confining pressure equal to the horizontal confining stress at the measurement point. Again, a strength reduction factor may be required to properly scale the laboratory values to true in situ strength values. Figures 5, 6, and 7 show the strength, vertical stress, and individual integrity factor, respectively, calculated for each measurement point at each stage of development. The figures also show the weighted average values at each development stage. The changes of the weighted average values over time are shown in figure 8.

The pillar stresses shown in figure 6 are significantly lower than the average stress obtained using the tributary-area concept. For 4.9-m-wide entries and 18-m-square pillars, the tributary-area stress concentration factor is 1.62. The premining vertical stress was estimated to be 7.2 MPa, using a value of 2.5 for the specific gravity of the overburden. Thus the estimated average

pillar stress is 1.62×7.2 , or 11.6 MPa. This value is approximately two times greater than the weighted average stresses determined from the BPC measurements. If indeed the measured stresses are less than the true stress values, then the calculated strength values will also be less than those corresponding to the true horizontal confining stresses. However, the relative difference between the calculated and true strengths will be less than the relative difference between the calculated and true confining stresses because of the characteristics of the triaxial strength curve (figure 4). Thus, the calculated integrity factors will be greater than the true integrity factors.

As an example, the calculated vertical and horizontal stresses were assumed to be 6 MPa and 2 MPa, respectively. From figure 4, the strength corresponding to a 2-MPa confining pressure is 40 MPa. Thus, the integrity factor (strength/load) is $40/6 = 6.7$. If the stresses calculated from the BPC data are 50% of the true stresses, then the true vertical stress would be 12 MPa and the true horizontal stress would be 4 MPa. The corresponding pillar strength at 4-MPa confinement is 52.5 MPa, resulting in a true integrity factor of $52.5/12 = 4.4$.

Because the average pillar stress determined using the tributary-area approach is significantly greater than the vertical stresses calculated from the BPC data, it seems unlikely that the actual pillar stress is as low as that indicated by figure 6. However, the values shown in figure 6 were used for all calculations to simplify presentation of the integrity factor approach. It should be recognized that the true integrity factors are likely to be somewhat less than those presented, although the differences should not affect the conclusions of this study.

ANALYSIS OF PILLAR STABILITY

The greatest variations of average weighted pillar strength, vertical stress, and integrity factor, shown in figure 8, occurred as the cave line approached the test area. In general, pillar strength and integrity factor decreased over time and vertical stress increased. To better visualize the strength and stress distributions along the pillar, cross sections of the strength and stress distributions along the pillar diagonals were plotted for each development stage. Figure 9 shows the pillar strength cross section. The sections indicate a general decrease in strength at the pillar edges (corners)

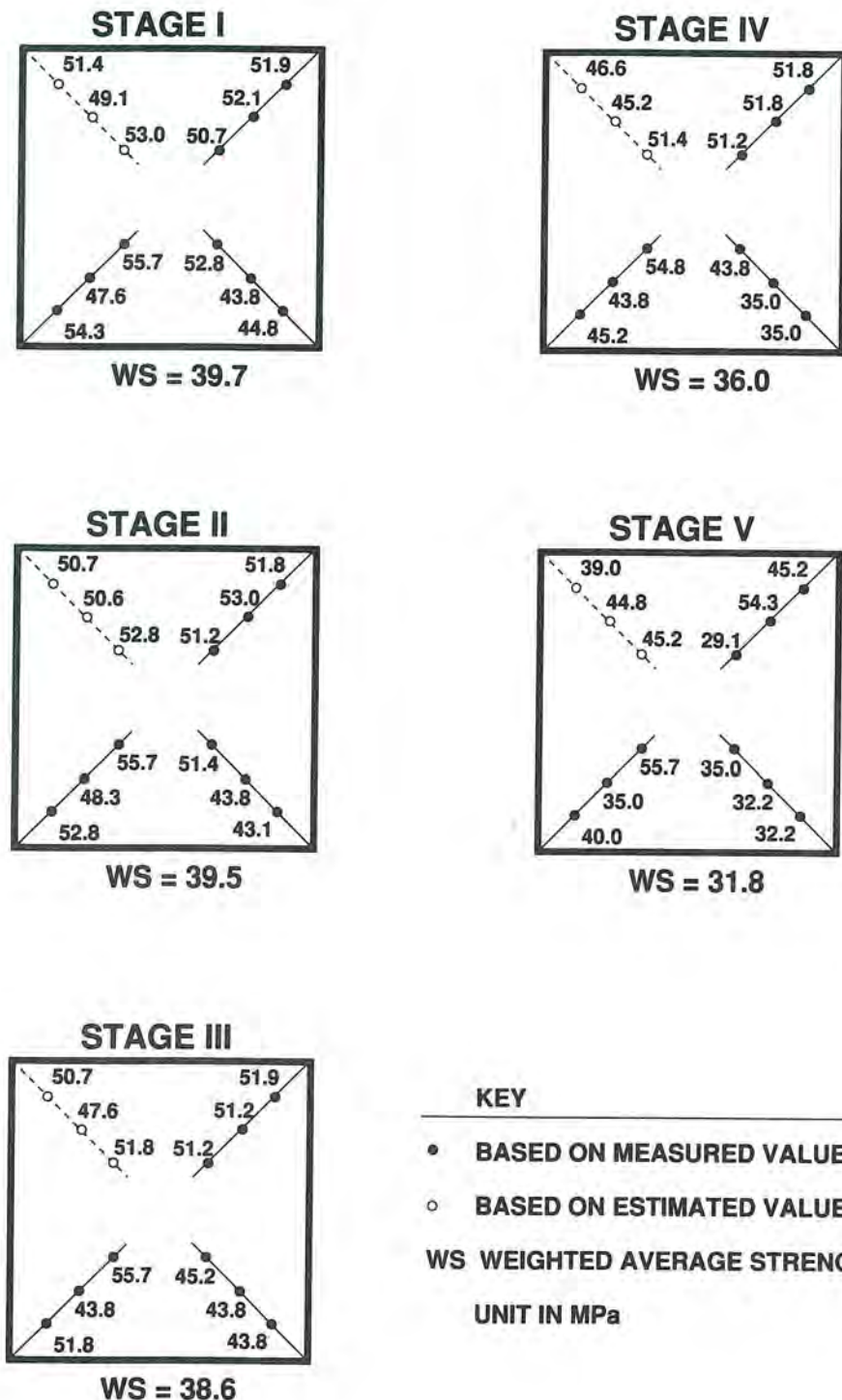


Figure 5. Distribution of pillar strength.

and either little change or a decrease in strength in the pillar core. The vertical stress cross sections shown in figure 10 show similar but more inconsistent behavior. The maximum vertical stress occurred at the pillar edge at the south corner during the first three development stages.

During retreat operations, the stress at the south corner decreased to a value less than the stress in the core region, suggesting a possible yielding, or partial failure, of the pillar corner. However, the strength values at the south corner did not change appreciably during Stage IV or Stage V, indicating that failure did not occur. The

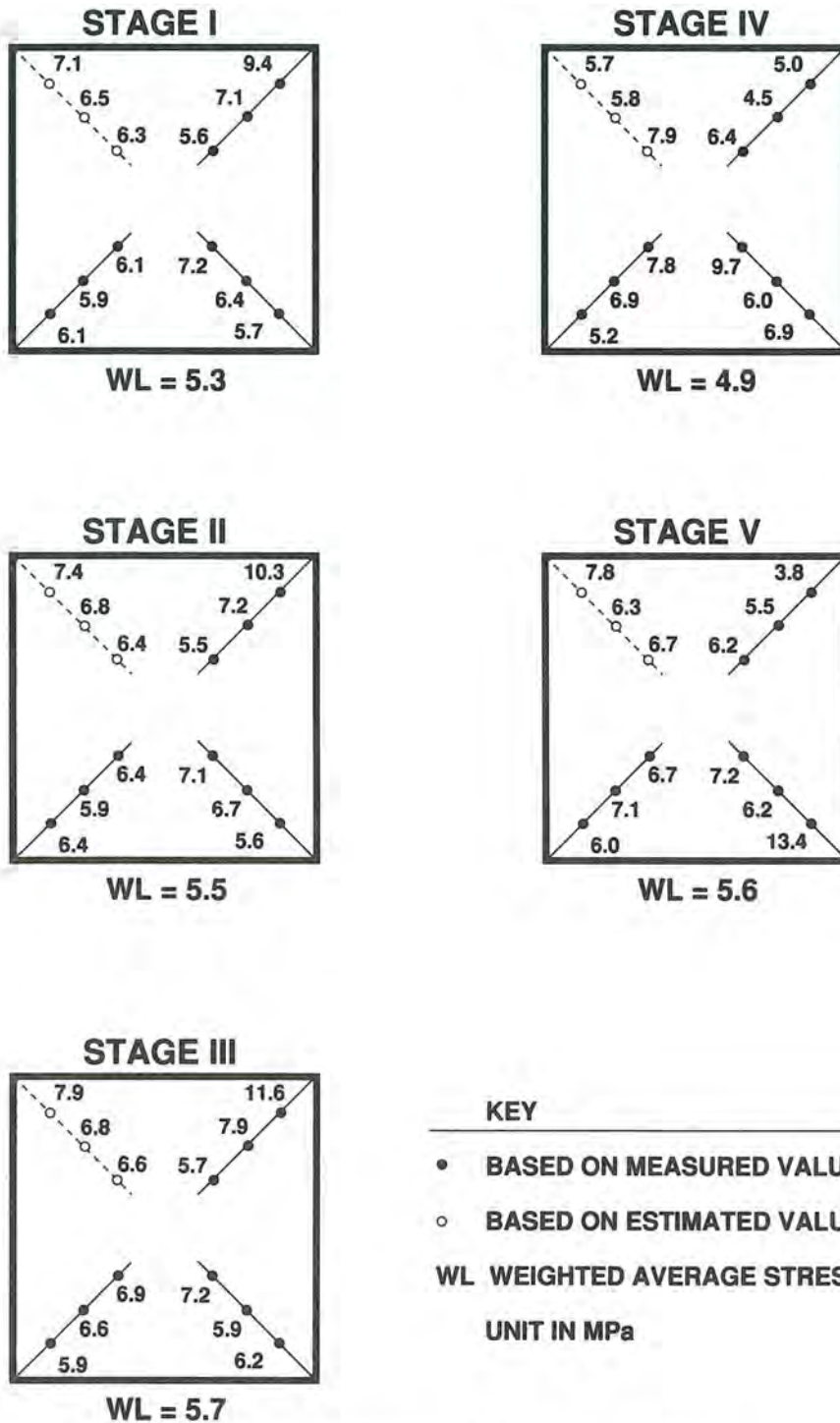


Figure 6. Distribution of vertical stress.

strength at the north and west corners steadily decreased over time, indicating a gradual deterioration of the outby

side of the pillar. As shown in figure 11, the minimum integrity factor, 2.4, occurs during Stage V at the west pillar

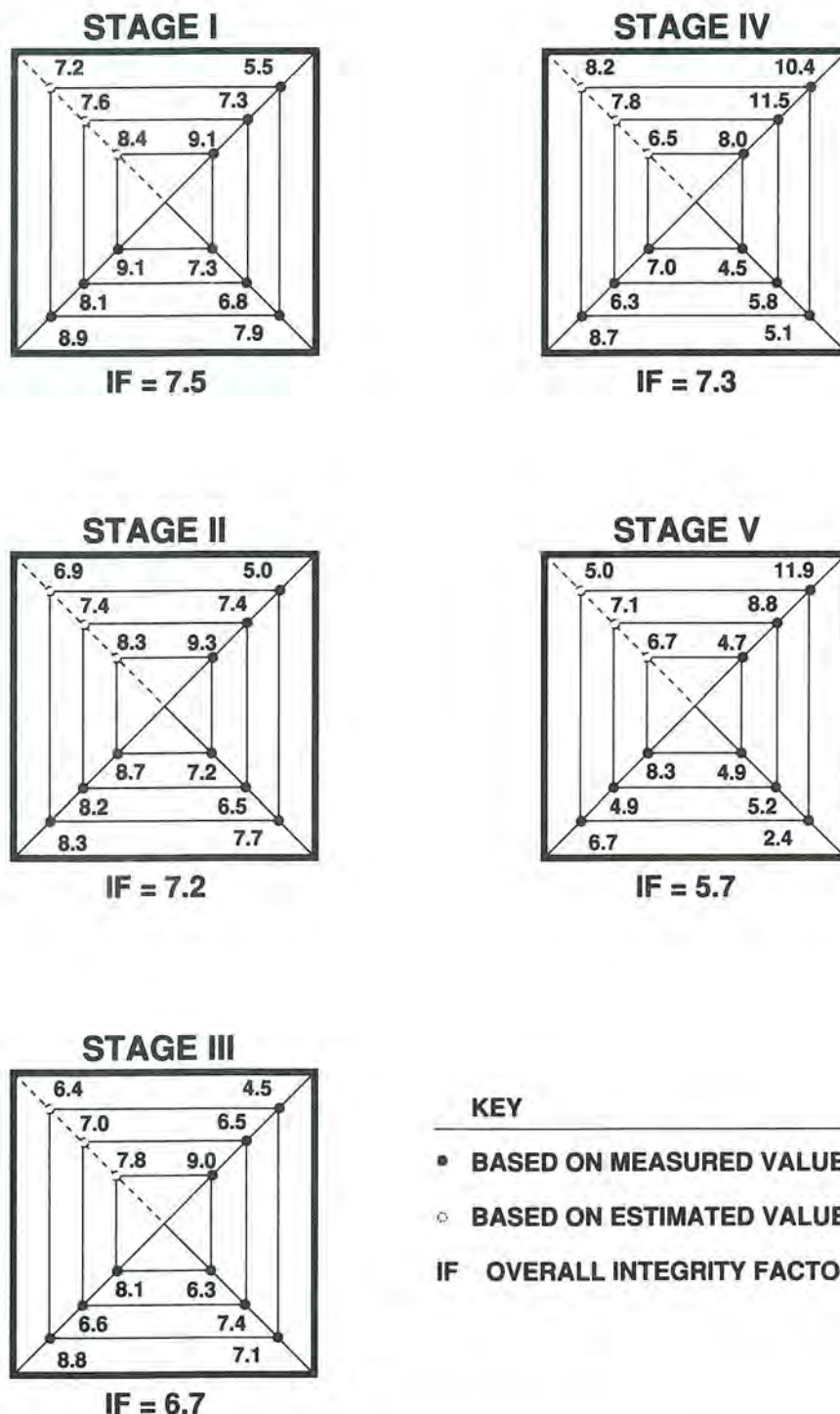


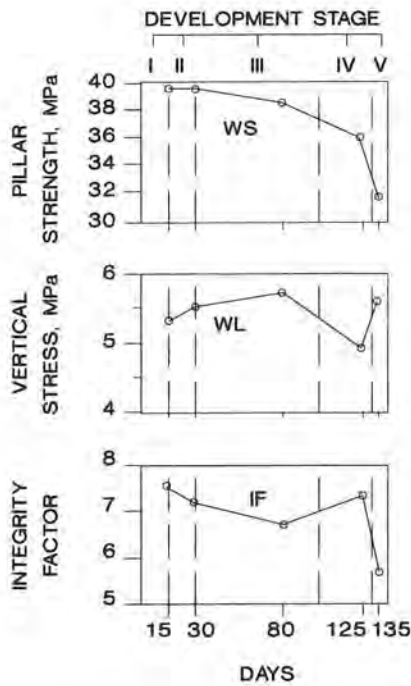
Figure 7. Distribution of individual integrity factors.

corner. Although the minimum integrity factor is greater than 1.0, it should not be concluded that the corner region is stable or that failure did not occur.

As discussed earlier, the calculated integrity factor may be too large due to

the apparently low stress values calculated from the BPC data. During Stage III, when the pillar was least influenced by mining activities, the weighted average vertical stress was 5.7 MPa. The average stress predicted by

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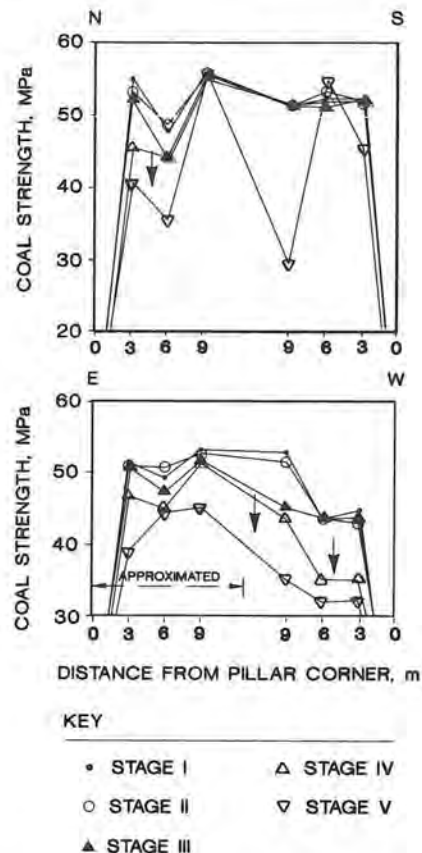
- WS WEIGHTED AVERAGE STRENGTH
- WL WEIGHTED AVERAGE STRESS
- IF OVERALL INTEGRITY FACTOR

Figure 8. Variation of strength, stresses, and integrity factor during development.

tributary-area calculations was 11.6 MPa; thus, the true ground stresses are expected to be greater than the calculated stresses by a factor of $11.6/5.7 = 2.0$. The calculated vertical and horizontal stresses were multiplied by this "adjustment" factor to determine adjusted stress values and the corresponding adjusted strengths and integrity factors. The minimum adjusted integrity factor occurs at the same location as the nonadjusted integrity factor, but its value is reduced from 2.4 to 1.5, only slightly greater than the expected failure value, 1.0. In addition, the integrity factors would be reduced still further if a strength reduction factor were applied to compensate for the expected difference between full-scale and laboratory-scale strength values. No substantial evidence of pillar failure was observed in the mine, indicating that the true integrity factors remained greater than 1.0 throughout the life of the pillar.

To maintain agreement with field observations, the strength reduction factor cannot exceed 1.5; however, common strength-scaling equations indicate that the reduction factor should be closer to approximately 5.0 (10). Using a strength reduction factor of 5.0 and a stress adjustment factor of 2.0 results in extremely low integrity factors (< 1.0) at most measurement points during all stages of development. Such low values are inconsistent with field observations. Therefore, the reduction factor of 5.0 is questionable. However, because the stress adjustment factor, 2.0, is somewhat arbitrary, it should not be concluded that a strength reduction factor is unnecessary.

Although a relatively large number of instruments were installed in the pillar, the resolution of the resulting strength, stress, and integrity factor distributions is limited. Both elastic theory and the confined-core theory (5) predict the occurrence of a stress peak at or near the pillar rib. The coarse spacing (3.0 m) of the measurement points is not sufficient to identify precisely the existence or location of this stress peak. Because failure is expected to initiate at a stress peak or other high-stress anomaly, accurate



KEY

- STAGE I △ STAGE IV
- STAGE II ▼ STAGE V
- ▲ STAGE III

Figure 9. Pillar strength cross sections.

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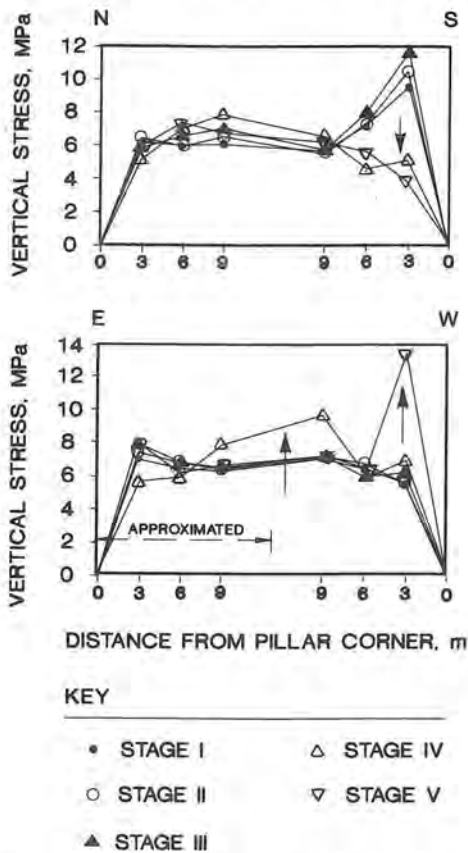


Figure 10. Vertical stress cross sections.

• characterization of the vertical and horizontal stress distributions is essential to understand the structural integrity of the pillar.

Future work should be directed toward determining the minimum acceptable instrument spacing and the optimum placement of instruments to adequately characterize the stress distributions throughout the pillar. Additional research is necessary to correlate BPC measurements to true pillar stresses and determine appropriate in situ strength-scaling factors.

Although the numerical values of the integrity factors are somewhat uncertain, the distributions of strength, vertical stress, and integrity factor show that considerable variation occurs within the pillar and throughout the life of the pillar. Conventional design methods based on a single safety factor may not adequately account for these spatial and time variations. In addition, other field-based approaches, using fewer measurement points, may misrepresent true stress conditions, resulting in either unsafe or excessively conservative designs.

CONCLUSIONS

Based on this limited analysis of a single test case, it appears that the integrity factor approach is a viable technique for evaluating pillar stability in room-and-pillar mines. The approach is based on distributions of estimated coal strengths and measured vertical stresses and can be used to analyze pillar stability throughout the life of the pillar. Thus, designs based on the integrity factor approach may more closely conform to actual conditions in the mine for optimum resource recovery, productivity, and safety.

It should be recognized that the integrity factor approach, particularly for room-and-pillar applications, is currently in an initial state of development. Because of the approximations involved in determining the in situ coal strength and the limitations associated with the stress measurement instruments, the accuracy of the calculated integrity factors is uncertain. In addition, the limited number of measurement points may not adequately resolve important details of

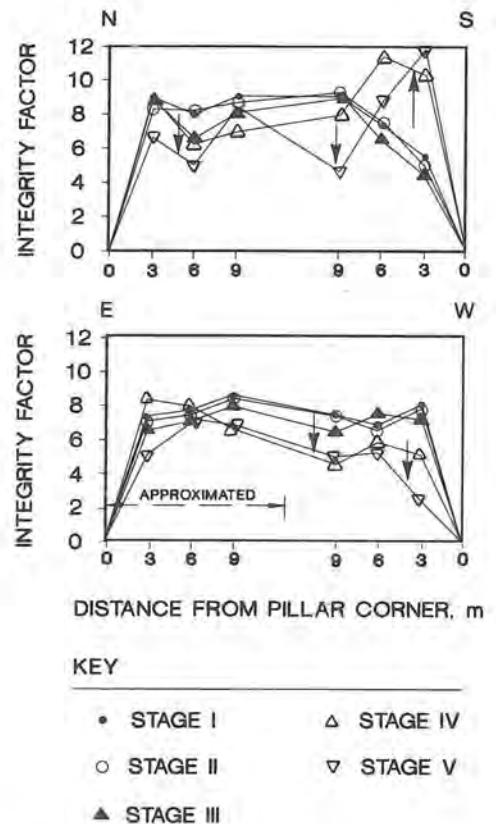


Figure 11. Individual integrity factor cross sections.

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the stress distributions, particularly near the ribs. Considerable effort yet remains to evaluate the measurement accuracy, to determine the optimum instrumentation layout, and to develop technical criteria for full utilization of the integrity factor approach to mine pillar design.

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7th International
Conference
August 3-5, 1988

Sponsored by
U.S. Bureau of Mines
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**Edited
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