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UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	lb/ft	pound per foot
ft	foot	lb/ft^3	pound per cubic foot
ft^2	square foot	pct	percent
in	inch	psi	pound per square inch

DISCLAIMER OF LIABILITY

ANALYSIS AND DESIGN CONSIDERATIONS FOR SUPERIMPOSED LONGWALL GATE ROADS

By Gregory J. Chekan[1] and Jeffrey M. Listak[1]

ABSTRACT

The U.S. Bureau of Mines is investigating longwall panel layouts to maximize coal recovery and minimize interactive problems in multiple-seam operations. When coalbeds are longwall mined in descending order, the transfer of stress from overlying gate roads is a major design constraint affecting pillar stability in the lower mine. The lower mine gate road pillars must be properly designed to withstand the additional load transfer if gate roads are superpositioned in successive seams. The Bureau's MULSIM/NL model, a boundary element computer program, was used to analyze load transfer mechanics for superpositioned gate road pillars. Analysis of Longwall Pillar Stability (ALPS), an empirically based design method for longwall gate road pillars, was used to calibrate model input parameters. ALPS provided a basis to verify model trends and to recommend limits for safe pillar design when superpositioning longwall gate roads.

The attributes of the MULSIM/NL model and ALPS were combined to develop a modified method for estimating pillar stress for multiple-seam cases. The modified method uses a multiple-seam factor (MS) to estimate the stress on superpositioned lower mine gate road pillars. Numerical analysis shows that MS depends on the interburden thickness and pillar width.

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INTRODUCTION

Longwall mining in the Appalachian Coal Region is becoming more economically advantageous as experience in its use is gained. The high productivity of longwall mining illustrates its potential to be the future of underground coal production. The high extraction efficiency and coal recovery of longwall mining make this system very advantageous compared with room-and-pillar methods in reducing interactions between multiple-seam mines.

There are two fundamental planning decisions a longwall operator must make when mining multiple seams: first, the order or sequence in which the seams will be mined and, second, whether the gate road pillars will be offset or superimposed. A descending order of mining is preferable, because the severe ground problems associated with subsidence interactions should be avoided in most cases (*1-4*).[2] The decision to offset or superimpose gate roads when mining multiple seams has been a topic of much concern in longwall design. Model studies have shown that superpositioning of gate roads produces the most adverse stress conditions on the gate road pillars and that in most cases offsetting pillars is preferable (*5*). However, there may be instances in which superpositioning of gate roads is required. Offset gate roads may create high stress concentrations on the longwall face, causing unacceptable production delays. Geologic factors, such as faults or sandstone channels within the coalbed, may render a block of coal unminable, thereby shifting gate roads to a superpositioned arrangement. Superpositioning may also be required near the perimeter of a coal property to maximize recovery. Contingency plans to superposition gate roads may be adopted under these special circumstances, but pillars must be properly designed to contend with load transfer from the overlying gate road pillars.

The major advantage of offsetting is that the gate roads in the lower mine can be developed under the upper mine gob, as shown in figure 1. When offsetting is practiced, designing pillars as in a single-seam case should be sufficient, because, with offsetting, load from overlying pillars is transferred to the longwall panel. This may or may not be a desirable situation, depending on the magnitude of the resultant stress concentration on the longwall face and the ability of the longwall supports to withstand this additional load.

When gate roads are superpositioned, as shown in figure 2, the longwall face has the advantage of operating beneath the upper mine gob, but gate road pillars must then be properly designed to withstand load transfer from the upper mine. The purpose of this study, conducted by the U.S. Bureau of Mines as part of its health and safety program, was to develop a method for estimating the magnitude of load transfer on the lower mine gate road pillars when superpositioning is practiced. This method should assist longwall operators in formulating mining plans and sizing pillars in the lower mine.

The use of numerical methods for predicting interactive problems is receiving more attention from researchers for application as a design and planning tool. Numerical methods, combined with case study results and theoretical and statistical analyses, can be used to develop optimum mining plans for different multiple-seam conditions. The computer programs MULSIM/NL and Analysis of Longwall Pillar Stability (ALPS) were used in this research to develop multiple-seam mining plans specifically for superimposed longwall gate roads.

MULSIM/NL is a boundary element model, developed by the Bureau, for calculating stresses and displacements in tabular deposits (*6*). The model provides the capability to analyze many coal mining situations and to determine the effects of the three-dimensional stress redistributions caused by mining in either single or multiple seams. The program can be used to evaluate the following: safe pillar sizes, ground control problems caused by stress concentrations, the effects of different geomechanical properties and in situ stress fields, load transfer from adjacent mining operations or multiple seams, entry deformations, and energy changes resulting from pillar development and extraction.

ALPS (*7*) is a design method developed by Bureau researchers that can estimate the strength of longwall pillar systems and the loads applied to them. This method is empirically based, and it has been verified by back-analysis of more than 100 case studies. ALPS was used to calibrate the MULSIM/NL model to generate baseline data for a single-seam case. These baseline data were then used to estimate load transfer and safe pillar designs when two seams are longwall mined.

Safe and productive longwall mining in multiple-seam situations requires that gate roads be properly designed to withstand the loads applied to them. The development of design methods based on numerical models has considerable potential in helping operators find solutions to complex multiple-seam interactive problems. The application of modeling methods coupled with sound engineering judgment and experience will improve coal conservation, resource recovery, and the health and safety of miners.

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[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

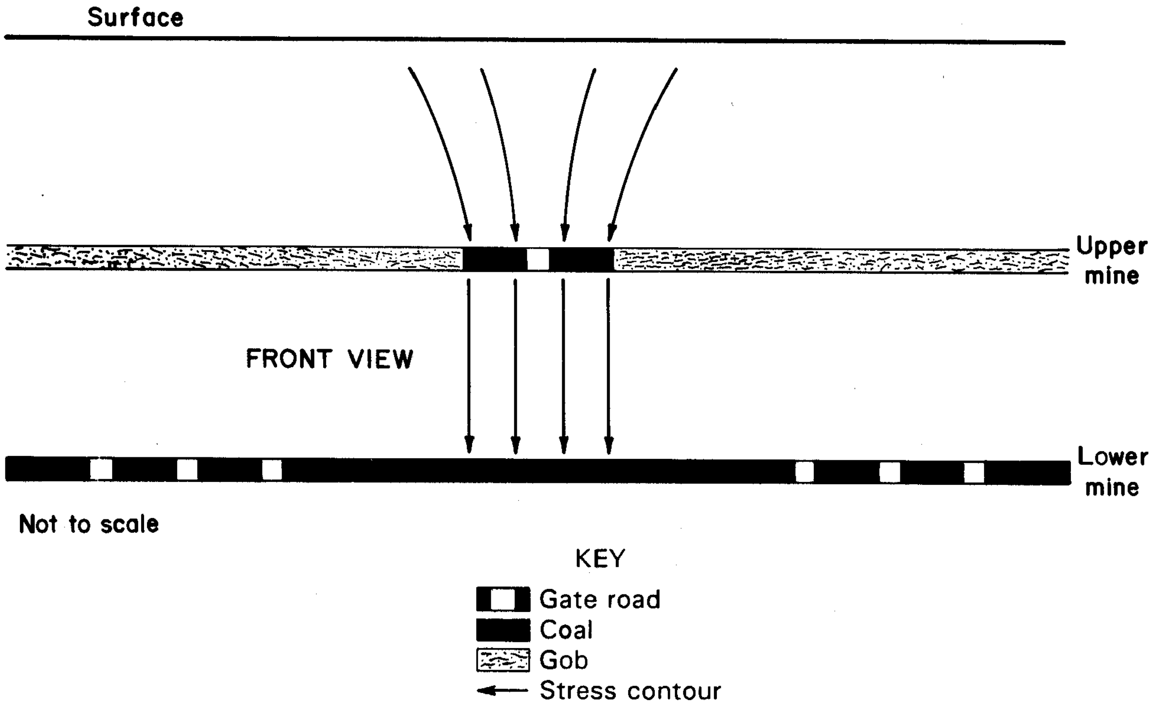

Figure 1.—Longwall panel and gate roads offset.

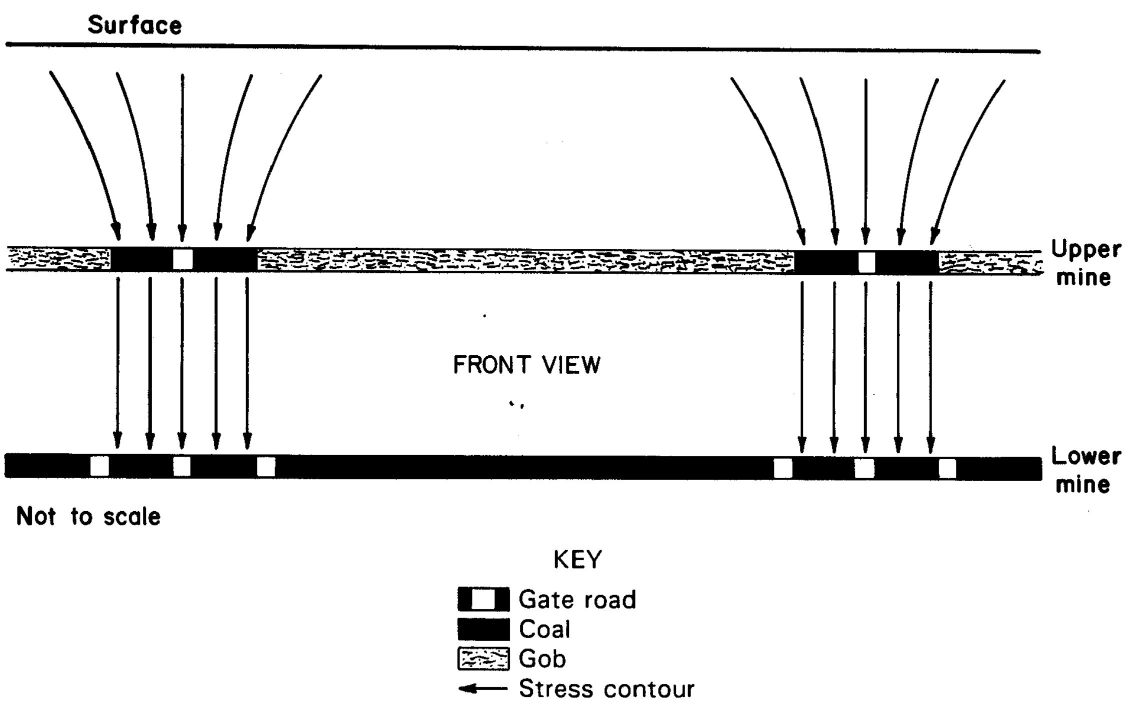

Figure 2.—Longwall panel and gate roads superimposed.

ENGINEERING DESIGN AND GEOLOGIC INPUT PARAMETERS

In the Eastern Coal Region, geologic conditions are best described as anisotropic. Depth, interburden thickness and other physical characteristics, and coalbed thickness vary widely among the different geologic regions. Mines in some extreme geologic environments, such as those associated with bumps, require specialized design techniques to contend with seam interaction. In this study, engineering and geologic parameters more typical of the Eastern Coal Region were selected for analysis. The engineering and geologic parameters designated for this study are given below with basis for their selection.

LONGWALL PANEL AND PILLAR DIMENSIONS

The longwall panel and pillar dimensions used in this study were chosen to generally represent current conditions in the field. The 1991 longwall census from Coal Magazine (*8*) was used as a basis for selection. The critical dimension for the longwall panel, as used in the model, is the panel width. There were 96 operating longwall faces in 1990, with 14 pct in the 500- to 599-ft range, 31 pct in the 600- to 699-ft range, 35 pct in the 700- to 799-ft range, 14 pct in the 800- to 899-ft range, and 6 pct in the 900- to 1,000-ft range. The average panel width was approximately 707 ft. Based on these figures, a panel width of 700 ft was selected for analysis in the model.

The census (*8*) also shows that 40 pct of the operators use a three-entry gate road, 34 pct use a four-entry gate road, 3 pct use other configurations, and the configurations used by the remaining 23 pct are unknown. Based on these figures and to narrow the extent of the investigation, both three- and four-entry gate roads with equal-sized pillars were selected for study. To cover a representative sample of pillar sizes in the field, pillar widths ranging from 50 to 100 ft were evaluated using the model.

GEOLOGIC INPUT PARAMETERS

The geologic parameters include depth, interburden characteristics, coalbed characteristics, in situ stresses, and geologic discontinuities. Of these, depth and interburden characteristics, which include thickness, strength, and elastic modulus, are the critical factors influencing stress transfer. Statistical analysis of case study information and photoelastic model results show that interactive probability is most sensitive to the relationship between depth and interburden characteristics (*9*). The next most important parameter is coalbed characteristics, which include thickness, coal strength, and dip, because these factors influence the loading behavior of the pillars. In situ stresses, such as a high horizontal stress, may affect overall stress magnitude, but the transfer of stress is more directly related to the normal cover load, which is a function of depth. Geologic discontinuities, such as clay veins, are more likely to cause localized instability in the workings than to affect the overall transfer of stress.

For this study, the MULSIM/NL model has two shortcomings. First, geologic discontinuities cannot be represented in the model. Second, individual strata that characterize the overburden and interburden cannot be represented, so a generic modulus is chosen that depicts the overall lithology. Assuming that the overburden and interburden are one homogeneous, isotopic material makes the strata reactions stiffer than is actually the case. Therefore, the elastic modulus of the material is lowered to more closely approximate a stratified rock mass. Physical properties of strata in the MULSIM/NL model are represented by the elastic modulus and Poisson's ratio. Elastic modulus values, in pounds per square inch, for the overburden and interburden, coal, and gob are given below. A Poisson's ratio of 0.25 was assumed for all cases.

Overburden and interburden	800,000
Coal	300,000
Gob	1,500

The coalbeds were assumed to be 6 ft thick. This figure was chosen because it represents an average operating height from a recent survey of longwall productivity (*8*). The coalbeds were also assumed to be flat-lying deposits with no dip. The assumed density of the overburden was 162.5 lb/ft^3.

CALIBRATING THE MODEL TO ALPS

ALPS (*7*) is a design method that estimates the strength of longwall gate road pillars and the stress they experience during development and mining of the longwall panels. ALPS was used to calibrate the MULSIM/NL model, because ALPS is empirically based on field measurements conducted at 16 longwall panels, and has been verified by back-analysis of over 100 case histories. The basic approach was to use the best attributes of both ALPS and the MULSIM/NL model to determine the magnitude of stress transfer between gate road pillars. ALPS' strength lies in its ability to estimate different abutment stresses and pillar stability factors at each stress condition. The MULSIM/NL model's strength is its ability to develop relative trends and to calculate the magnitude of stress transfer between workings. The combination of these two attributes was used to estimate the magnitude of stress that the lower mine gate road pillars would experience.

ALPS analyzes five stress conditions that gate road pillars experience as the first and second longwall panels are mined. Stress is calculated as the total load divided by the load-bearing area of the pillar. These stress conditions are as follows: (1) the development stress, which occurs when the gate road pillars are initially mined; (2) the headgate stress, which occurs when the first panel is directly adjacent to the target pillar; (3) the bleeder stress, which occurs when the first panel has been mined; (4) the tailgate stress, which occurs when the second panel is adjacent to the target pillar; and (5) the isolated stress, which occurs when the second panel has been mined. Conditions 2 through 5 are each separate stresses and they must be added to the development stress to obtain the total stress for that condition.

As shown in figure 3, the stress conditions that apply for analyzing superpositioned gate roads are 1 and 5 for the upper mine and 1 for the lower mine. ALPS was used to calibrate the MULSIM/NL model for these conditions. The model was calibrated assuming a 21° abutment angle on a 700-ft-wide panel, and using a three-entry gate road consisting of two 60- by 80-ft pillars and 20-ft-wide entries at 750 ft of depth. At this depth, the pillars have an ALPS stability factor of 1.0 at isolated loading. Stability factors ranging from 1.0 to 1.3 are recommended for sizing pillars for tailgate protection using ALPS (*7, 10*). Through a systematic procedure, MULSIM/NL input was gradually modified until the best fit was achieved for the two stress conditions. To illustrate, MULSIM/NL predicted 91.2 pct of the average pillar stress calculated by ALPS at development. For the isolated case, the MULSIM/NL model fit was 89.1 pct of the predicted ALPS average pillar stress. An exact match to ALPS could not be achieved by the MULSIM/NL model without making input parameters unrealistic. Two factors were responsible for this. First, in most boundary element models, some stress is lost along the boundaries of the model. Second, the model places more stress on the adjacent longwall panel than ALPS does because of the inherent lateral stiffness of the homogeneous, isotropic overburden assumed in MULSIM/NL. However, achieving an exact match was not necessary since, in the final analysis, model output from the multiple-seam results was normalized to these single-seam results.

The model input parameters for overburden, interburden, coal, and gob that best resembled output data

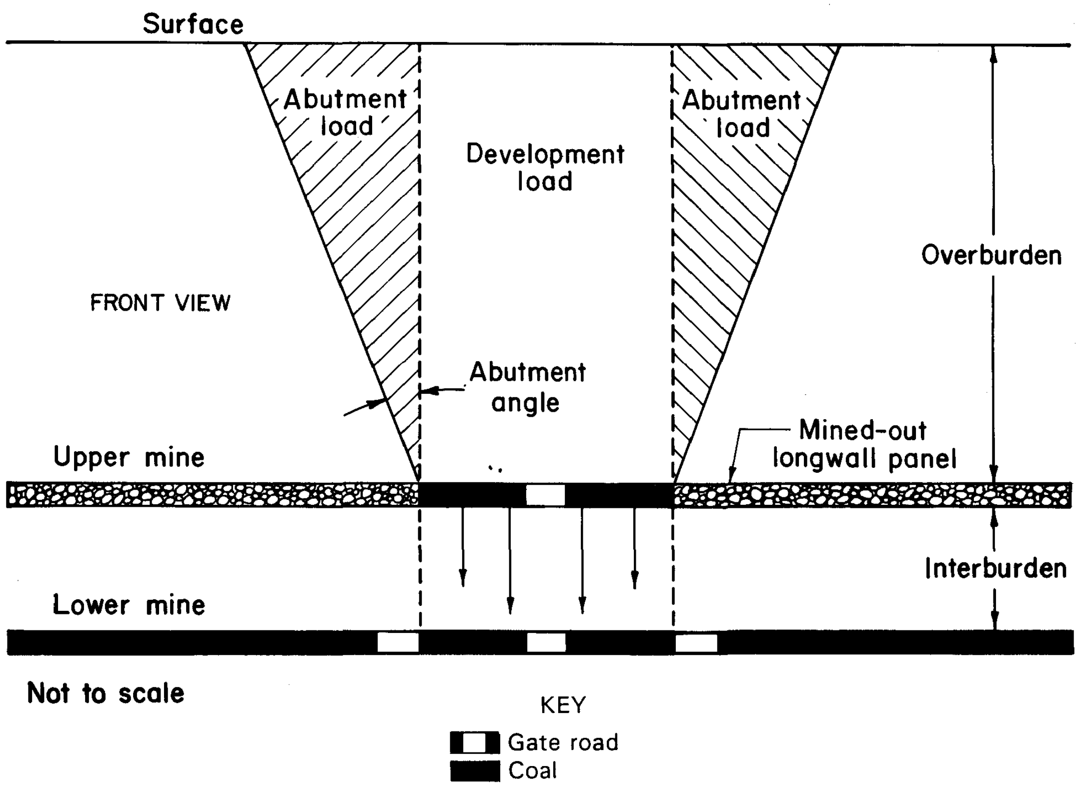

Figure 3.—Stress conditions for upper and lower mine when gate roads are superimposed.

from ALPS are given in the previous section on geologic input parameters. All model input parameters were assigned linear elastic property codes to best simulate the behavior of the ALPS method. ALPS failure criterion assumes that the pillars do not yield, but instead support the weight of the different stress conditions until these stresses exceed the strength of the pillar. The stability of the pillar, which is represented in ALPS as a stability factor, becomes critical as the factor approaches 1.0 to 1.3.

ANALYSIS OF SUPERPOSITIONED GATE ROADS

The analysis of superimposed gate roads assumes that mining is completed in the upper seam with gob on both sides of the gate roads and that the pillars in both seams are of equal size. As shown in figure 3, the stress on the upper mine pillars is equal to the development stress at that depth plus the stress generated by the two side abutment loads. The stress on the lower seam pillars is equal to the development stress at that depth plus a certain percentage of the stress that is transferred from the upper mine pillars. To determine the percentage of stress that is transferred from the upper to the lower mine the following equations are used.

For the upper mine:

$$\sigma_{au} = \sigma_{iu} - \sigma_{du}, \tag{1}$$

where σ_{au} = abutment stress for upper mine pillars, psi,

σ_{iu} = isolated stress for upper mine pillars, psi,

and σ_{du} = development stress for upper mine pillars, psi.

For the lower mine:

$$\sigma_t = \sigma_{tl} - \sigma_{dl}, \tag{2}$$

where σ_t = amount of stress transferred to lower mine pillars, psi,

σ_{tl} = total stress on lower mine pillars, psi,

and σ_{dl} = development stress for lower mine pillars, psi.

Also,

$$MS = \frac{\sigma_t}{\sigma_{au}}, \tag{3}$$

where MS = multiple-seam factor, which is the percentage of abutment stress transferred from the upper to the lower mine pillars.

The MULSIM/NL model generates stress values for σ_{iu}, σ_{du}, σ_{tl}, and σ_{dl}. Values for σ_{au} and σ_t are calculated from equations 1 and 2, and MS, for a given interburden, is calculated from equation 3.

These three equations were used to analyze the effects of varying depths, interburden thicknesses, and pillar sizes on MS. All analyses assumed a three-entry gate road with 20-ft-wide entries. The analysis was first conducted for a 60- by 80-ft pillar at an interburden of 50 ft for depths ranging from 300 to 800 ft for the lower mine. A depth of 800 ft represents the design limitation for a 60- by 80-ft pillar using ALPS, because the stability factor at this depth is approximately 1.0 at tailgate loading.

The results of this analysis are given in table 1. These data show that for a 60- by 80-ft pillar and at 50 ft of interburden between the mines, MS has little variation, ranging between 0.69 and 0.71. This lack of variation indicates that when interburden is kept constant MS is independent of depth.

To determine if pillar length and percent extraction affect this factor, the pillar width was kept constant at 60 ft and length was increased to 120 ft. The extraction is 40 pct for a 60- by 80-ft pillar and 36 pct for a 60- by 120-ft pillar. The results for a 60- by 120-ft pillar are given in table 1. As shown, MS had little variation, indicating that, within the range of variables tested, MS is independent of the pillar length and percent extraction.

To determine if pillar width affects MS, the width was increased to 100 ft. The same analysis was performed on a 100- by 100-ft pillar keeping the interburden at 50 ft. The depths ranged from 700 to 1,400 ft for the lower mine, because the stability factor at the greater depth is approximately 1.0 at tailgate loading. Table 1 shows the results of this analysis. MS in this case was higher (0.76), indicating that MS varies slightly depending on the width of the pillar.

To determine how interburden thickness affects MS, the same analysis was performed on a 60- by 80-ft and a 100- by 100-ft pillar, but changing the interburden to 25 ft. The results for each pillar are given in table 2. MS increased to 0.87 for the 60- by 80-ft pillar and to 0.89 for the 100- by 100-ft pillar, indicating that MS is very sensitive to the interburden thickness.

Table 1.—Multiple-seam factor (MS) for pillars at varying depths with interburden of 50 ft

Pillar size and MS (σ_t/σ_u)	Upper mine				Lower mine			
	Depth, ft	σ_{iu}, psi	σ_{du}, psi	σ_{au}, psi	Depth, ft	σ_{tl}, psi	σ_{dl}, psi	σ_t, psi
60- by 80-ft pillar:								
0.71	250	1,075	428	647	300	970	514	456
0.70	350	1,520	599	921	400	1,330	685	645
	450	1,966	771	1,195	500	1,689	857	832
0.69	550	2,410	942	1,468	600	2,046	1,028	1,018
	650	2,850	1,114	1,736	700	2,404	1,200	1,204
	750	3,294	1,285	2,009	800	2,763	1,371	1,392
60- by 120-ft pillar:								
0.71	250	1,057	407	650	300	945	488	457
	350	1,483	569	914	400	1,299	651	648
	450	1,919	732	1,187	500	1,653	813	840
	550	2,351	895	1,456	600	2,004	976	1,028
	650	2,785	1,058	1,727	700	2,356	1,139	1,217
0.70	750	3,214	1,221	1,993	800	2,706	1,302	1,404
100- by 100-ft pillar:								
0.76	650	2,176	999	1,177	700	1,969	1,075	894
	750	2,515	1,151	1,364	800	2,262	1,229	1,033
	850	2,851	1,306	1,545	900	2,554	1,382	1,172
	950	3,190	1,460	1,730	1,000	2,847	1,536	1,311
	1,050	3,526	1,613	1,913	1,100	3,138	1,690	1,448
	1,150	3,865	1,766	2,099	1,200	3,432	1,843	1,589
	1,250	4,202	1,920	2,282	1,300	3,723	1,996	1,727
	1,350	4,541	2,074	2,467	1,400	4,017	2,150	1,867

Table 2.—Multiple-seam factor (MS) for pillars at varying depths with interburden of 25 ft

Pillar size and MS (σ_t/σ_u)	Upper mine				Lower mine			
	Depth, ft	σ_{iu}, psi	σ_{du}, psi	σ_{au}, psi	Depth, ft	σ_{tl}, psi	σ_{dl}, psi	σ_t, psi
60- by 80-ft pillar:								
0.87	275	1,184	471	713	300	1,135	514	621
0.86	375	1,626	642	984	400	1,539	685	845
	475	2,064	814	1,250	500	1,940	857	1,083
	575	2,506	985	1,521	600	2,344	1,028	1,316
	675	2,946	1,156	1,790	700	2,746	1,200	1,546
	775	3,386	1,327	2,059	800	3,150	1,371	1,779
100- by 100-ft pillar:								
0.89	675	2,253	1,037	1,216	700	2,161	1,075	1,086
	775	2,587	1,192	1,395	800	2,475	1,229	1,246
	875	2,925	1,345	1,580	900	2,792	1,382	1,410
	975	3,259	1,498	1,761	1,000	3,106	1,536	1,570
	1,075	3,597	1,651	1,946	1,100	3,424	1,690	1,734
	1,175	3,932	1,805	2,127	1,200	3,738	1,843	1,895
	1,275	4,270	1,958	2,312	1,300	4,055	1,996	2,059
	1,375	4,604	2,112	2,492	1,400	4,371	2,150	2,210

The above analysis showed that the two most important parameters influencing MS, in order of sensitivity, are interburden thickness and pillar width. Model runs were then performed for interburdens ranging from 25 to 300 ft in 25-ft increments and for pillar widths ranging from 50 to 100 ft in 10-ft increments. The depth to the lower seam was kept constant, because table 1 shows that depth does not influence MS. The depth selected for a particular pillar size was based on the stability factor of 1.0 for tailgate loading using ALPS. For instance, for a pillar width of 80 ft, an 80- by 80-ft pillar was modeled. This pillar reaches a stability factor of 1.0 at tailgate loading at a depth of 1,100 ft. Therefore, for the first model run the lower mine depth was kept constant at 1,100 ft and the depth to the upper mine was 1,075 ft, giving an interburden of 25 ft. For the second model run the lower mine was again kept constant at 1,100 ft, and the depth to the upper mine was changed to 1,050 ft, giving an interburden of 50 ft. This procedure was continued until an interburden of 300 ft was reached. At 300 ft of interburden, stress dissipation was such that MS became negligible—less than 0.15 for all pillar widths. Table 3 shows how MS was generated for a 60- by 80-ft pillar at each interburden using equations 1, 2, and 3.

Table 3.—Multiple-seam factor (MS) for 60- by 80-ft pillar at varying interburdens

(MS σ_l/σ_{au})	Upper mine				Lower mine				
	Depth, ft	σ_{iu}, psi	σ_{du}, psi	σ_{au}, psi	Interburden, ft	Depth, ft	σ_{tl}, psi	σ_{dl}, psi	σ_l, psi
0.86	775	3,386	1,327	2,059	25	800	3,150	1,371	1,779
0.69	750	3,294	1,285	2,009	50	800	2,763	1,371	1,392
0.48	725	3,231	1,242	1,989	75	800	2,325	1,371	954
0.39	700	3,138	1,200	1,938	100	800	2,117	1,371	746
0.31	675	3,046	1,156	1,890	125	800	1,947	1,371	576
0.24	650	2,948	1,114	1,834	150	800	1,807	1,371	436
0.18	625	2,844	1,071	1,773	175	800	1,693	1,371	322
0.14	600	2,735	1,028	1,707	200	800	1,603	1,371	232
0.10	575	2,627	985	1,642	225	800	1,528	1,371	57
0.06	550	2,519	942	1,577	250	800	1,469	1,371	98
0.03	525	2,408	900	1,508	275	800	1,421	1,371	50
0.01	500	2,292	857	1,435	300	800	1,384	1,371	13

Figure 4 shows the data generated from these analyses. These graphs are used in conjunction with ALPS to estimate the development stress on the lower mine pillars and resulting stability factors.

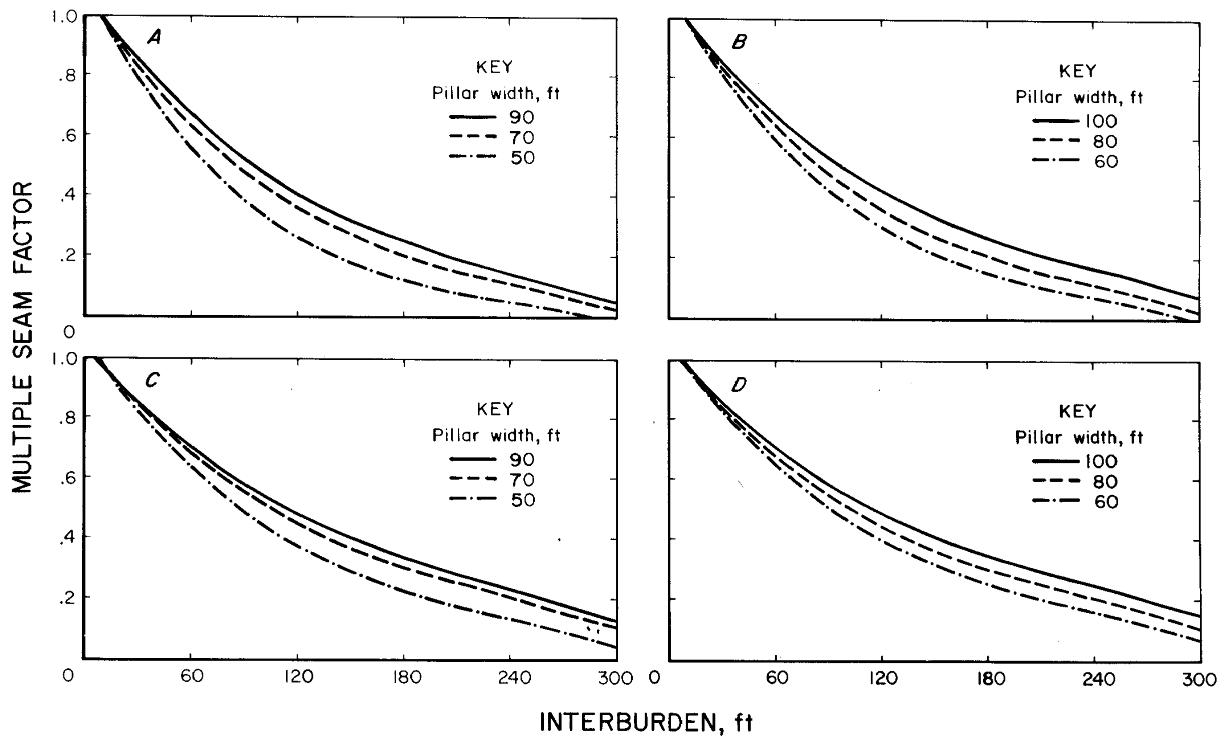

Figure 4.—Multiple-seam factor for three-entry (A-B) and four-entry (C-D) gate roads.

USING THE MULTIPLE-SEAM FACTOR

The MS values in figure 4 must be used in conjunction with ALPS to estimate the development load on the lower mine gate road pillars. Details on the ALPS method are contained in Bureau IC 9247 (*4*), which includes an appendix that gives step-by-step guidelines for using ALPS in a single-seam case. From the stresses calculated using ALPS, the multiple-seam stresses can be determined. ALPS is also available as user-friendly software, which can be obtained from the Bureau upon request.[3] The software is accompanied by a user's guide that provides instructions for using the program and interpreting the output. A step-by-step example of how to use the output generated from ALPS to estimate the multiple-seam stresses and stability factors on the lower mine gate road pillars is given below.

Problem

Mine A, the upper mine, has an average overburden of 800 ft. The mine uses a three-entry gate with 70- by 80-ft pillars and 20-ft-wide entries. The longwall panel is 700 ft wide. The lower mine, Mine B, will also use the same size pillars and entries, and the gate roads will be superpositioned as shown in figure 2. The mining height in both seams is 6 ft. The interburden between the two mines is 50 ft. Determine the stress on the lower mine pillars during development and the resulting stability factors.

Solution

Step 1: Figure 5 gives an example of the output from the ALPS program for the upper mine once the above information is entered into the "analysis mode." Figure 6 gives the output for the lower mine. The first part of the calculations involves using the "development loading" and "isolated loading" for the upper mine. These values are found in figure 5 under the heading "Additional Output" and subheading "Design Loadings On Pillar System." In this example, the development loading for the upper mine is 0.234E+08 lb/ft of gate entry, and the isolated load is 0.632E+08 lb/ft of gate entry.

Step 2: The next step is to convert these linear loads to a force per unit area, pounds per square inch, using the following equations:

$$\sigma_d = \frac{L_d \cdot C}{144 \cdot A_{pt}}, \tag{4}$$

and

$$\sigma_i = \frac{L_i \cdot C}{144 \cdot A_{pt}}, \tag{5}$$

[3]A copy of the program can be obtained by sending one double-sided, double-density diskette to the Pittsburgh Research Center, U.S. Bureau of Mines, Cochrans Mill Road, Pittsburgh, PA 15236. Please reference this publication.

where σ_d = average stress on pillar due to development load, psi,

σ_i = average stress on pillar due to isolated load, psi,

L_d = development load, 0.234E+08 lb/ft,

L_i = isolated load, 0.632E+08 lb/ft,

C = crosscut spacing, 100 ft,

and A_{pt} = total area of pillars, 11,200 ft².

Substituting the values into the equations, the stress for the development load and the isolated load are 1,450 psi and 3,290 psi, respectively.

Step 3: The development stress is then subtracted from the isolated stress to yield the isolated abutment stress, which is 2,470 psi.

Step 4: The proper MS must be selected from the graphs in figure 4. In this example, refer to graph 44 for a three-entry gate road. The interburden is 50 ft and from the curve for a 70-ft-wide pillar the factor is approximately 0.72. This factor is then multiplied by the isolated abutment stress (2,470 psi) giving 1,780 psi, which is the amount of stress transferred to the lower mine pillars.

Step 5: Step 2 is repeated for the lower mine, using only the development load from figure 6, which is 0.248E+08 lb/ft of gate entry. Converting this linear load to a force per unit area using equation 4 gives 1,540 psi.

Step 6: The values in steps 4 and 5 are added: 1,780 psi + 1,540 psi = 3,320 psi. This value is the development stress on the lower mine pillars and accounts for the stress transferred from the overlying gate roads.

Step 7: This step involves calculating the pillar stability factor to determine if the pillar can adequately support the development stress. The unit pillar strength is divided by the development stress calculated in step 6. Several formulas are available for calculating unit pillar strength, the least conservative being the Bieniawski-Pennsylvania State University formula (*11*).

$$\sigma_p = \sigma_1 \left[0.64 + 0.36 \cdot \frac{w}{h}\right], \tag{6}$$

where σ_p = unit pillar strength, psi,

σ_1 = in situ coal strength, 900 psi (*7*),

w = least width of pillar, in,

and h = height of pillar, in.

```
**********  ANALYSIS OF LONGWALL PILLAR STABILITY (ALPS)   **********

NAME OF MINE                                      A Mine

MINING HEIGHT (ft)                                   6.0
MINING DEPTH (ft)                                    800
IN SITU COAL STRENGTH (psi)                          900
ABUTMENT ANGLE (deg)                                21.0
PANEL WIDTH (ft)                                     700
ENTRY WIDTH (ft)                                    20.0
CROSSCUT CENTER/CENTER (ft)                        100.0
ENTRY CENTER / CENTER (ft) - PILLAR 1               90.0
ENTRY CENTER / CENTER (ft) - PILLAR 2               90.0

           ******* ALPS STABILITY FACTORS *******

             DEVELOPMENT LOADING                  3.01
             HEADGATE LOADING                     2.13
             BLEEDER LOADING                      1.65
         *** TAILGATE LOADING                     1.23
             ISOLATED LOADING                     1.11

.......................ADDITIONAL OUTPUT.....................

FOR PILLAR WIDTH (ft)       =          70.0
AND PILLAR LENGTH (ft)      =          80.0
WIDTH/HEIGHT RATIO          =         11.67
UNIT PILLAR STRENGTH        =          4356
PILLAR LOAD BEARING CAPACITY (lbs per ft of gate entry)=   3.51E+07

TOTAL PILLAR SYSTEM LOAD BEARING CAPACITY
  (lbs per ft of gate entry) =        7.03E+07

    DESIGN LOADINGS ON PILLAR SYSTEM (lbs per ft of gate entry)

FOR DEVELOPMENT LOADING       =        0.234E+08
FOR HEADGATE LOADING          =        0.330E+08
FOR BLEEDER LOADING           =        0.426E+08
FOR TAILGATE LOADING          =        0.572E+08
FOR ISOLATED LOADING          =        0.632E+08

                 INDIVIDUAL PILLAR LOADING (psi)

LOADING          PILLAR       PILLAR       PILLAR       PILLAR
CONDITION          1            2            3            4

DEVELOPMENT       1448         1448          0            0
HEADGATE          2304         1751          0            0
BLEEDER           3160         2054          0            0

UNIT PILLAR
STRENGTH          4356         4356          0            0

NOTE:  INDIVIDUAL PILLAR LOADINGS DO NOT CONSIDER LOAD
       TRANSFER DUE TO PILLAR YIELDING!
```

Figure 5.—Output from ALPS program for upper mine.

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**********  ANALYSIS OF LONGWALL PILLAR STABILITY (ALPS)   **********

NAME OF MINE                                      B Mine

MINING HEIGHT (ft)                                  6.0
MINING DEPTH (ft)                                   850
IN SITU COAL STRENGTH (psi)                         900
ABUTMENT ANGLE (deg)                               21.0
PANEL WIDTH (ft)                                    700
ENTRY WIDTH (ft)                                   20.0
CROSSCUT CENTER/CENTER (ft)                       100.0
ENTRY CENTER / CENTER (ft) - PILLAR 1              90.0
ENTRY CENTER / CENTER (ft) - PILLAR 2              90.0

           ******* ALPS STABILITY FACTORS *******

             DEVELOPMENT LOADING                 2.83
             HEADGATE LOADING                    1.97
             BLEEDER LOADING                     1.51
         *** TAILGATE LOADING                    1.11
             ISOLATED LOADING                    1.01

........................ADDITIONAL OUTPUT.....................

FOR PILLAR WIDTH (ft)       =         70.0
AND PILLAR LENGTH (ft)      =         80.0
WIDTH/HEIGHT RATIO          =        11.67
UNIT PILLAR STRENGTH        =         4356
PILLAR LOAD BEARING CAPACITY (lbs per ft of gate entry)=   3.51E+07

TOTAL PILLAR SYSTEM LOAD BEARING CAPACITY
  (lbs per ft of gate entry) =        7.03E+07

    DESIGN LOADINGS ON PILLAR SYSTEM (lbs per ft of gate entry)

FOR DEVELOPMENT LOADING       =        0.248E+08
FOR HEADGATE LOADING          =        0.356E+08
FOR BLEEDER LOADING           =        0.465E+08
FOR TAILGATE LOADING          =        0.630E+08
FOR ISOLATED LOADING          =        0.698E+08

                INDIVIDUAL PILLAR LOADING (psi)

LOADING          PILLAR       PILLAR       PILLAR       PILLAR
CONDITION          1            2            3            4

DEVELOPMENT       1539         1539          0            0
HEADGATE          2480         1888          0            0
BLEEDER           3422         2237          0            0

UNIT PILLAR
STRENGTH          4356         4356          0            0

NOTE:  INDIVIDUAL PILLAR LOADINGS DO NOT CONSIDER LOAD
       TRANSFER DUE TO PILLAR YIELDING!
```

Figure 6.—Output from ALPS program for lower mine.

In this example, the least width of the pillar is 840 in, and the height of the pillar is 72 in. Substituting these values into equation 6 gives a unit pillar strength of 4,360 psi.

Step 8: To calculate the stability factor, the unit pillar strength value in step 7 is divided by the development stress in step 6: 4,360/3,320 = 1.3. The recommended stability factor for pillars using this formula ranges from 1.5 to 2.0 (*11*). By this analysis the 70- by 80-ft pillar in the lower mine is slightly underdesigned to accept the development stress as well as the additional stress that is applied as the longwall panels are mined.

There are two options to consider under these conditions. First, a larger pillar can be used in the lower mine. If the center entries are superimposed, this would cause the lower mine gate roads to be slightly offset in relation to the upper mine, thereby shortening the panel width. In this case, a pillar at least 80 ft wide would be required in the lower mine. Steps 1 through 4 for the upper mine would remain the same. Step 5 would require running ALPS for an 80- by 80-ft pillar and a 680-ft panel. This gives a development stress of 1,495 psi. Adding 1,780 psi from step 4, which is the amount of transferred stress, gives a development stress on the lower mine pillars of 3,275 psi. From step 7 the unit pillar strength is calculated to be 4,896 psi. From step 8 this gives a stability factor of 1.5.

Second, pillars can be designed in both mines simultaneously so similar sizes are achieved in both operations. This requires planning before mining begins and a conscious effort to longwall mine both seams knowing that pillars in the upper mine may be slightly overdesigned to achieve properly designed pillars in the lower mine. Working steps 1 through 8 for 80- by 80-ft pillars in both mines gives a stability factor of 1.6 for the lower mine pillars on development. Depending on local roof and floor conditions, this stability factor can be adjusted accordingly within the specified range of 1.5 to 2.0.

ALPS stability factors for development loading in a single-seam case are usually over 2.5. For instance, the stability factor for the 70- by 80-ft pillar at 850 ft of depth in the preceding example is 2.83 (fig. 6). In a single-seam case, this high stability factor is necessary to maintain a factor between 1.0 and 1.3 after both longwall panels are mined. In a multiple-seam case, the stability factors for development loading do not need to be as high. As shown in figure 7, part of the abutment load on the lower mine pillars after both panels are extracted (isolated load) is that transferred on development from the upper mine.

To further illustrate, MULSIM/NL was used to analyze the development and abutment stresses for both a single- and a multiple-seam case. The results are shown in figure 8. A three-entry gate road with 60- by 80-ft pillars, 20-ft-wide entries, and a 700-ft-wide panel was used in the analysis. The depth was 750 ft. The first model run was for a single-seam case to attain stress values for the five different stress conditions. The second model run was for a multiple-seam case. The mine depth remained at 750 ft with a similar set of gate roads 50 ft above. As shown, the development stress in the multiple-seam case is more than twice that of the single-seam case; the stability factor is 2.9 for the single-seam case and approximately 1.5 for the multiple-seam case. However, at isolated loading the stability factors are nearly equal at 1.1.

SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to determine if changing the model input parameters would affect MS. Elastic modulus values for the rock mass, coal, and gob were increased and decreased by 25 pct from the values given in the "Geologic Input Parameters" section. For instance, the rock mass elastic modulus in the original model was 800,000 psi. Model runs were made with the modulus at 1 million psi and then at 600,000 psi. The seam height was also increased and decreased from 6 ft with model runs made at 4 ft and 8 ft.

The analysis was performed on a three-entry gate road using 60- by 80-ft pillars, 20-ft-wide entries, and a 700-ft panel. This analysis showed that the stress values for pillars would change, but this had little effect on MS when the data were normalized. Changes in the rock mass and coal modulus values followed similar trends. Increasing the modulus increased the multiple-seam pillar stresses, and decreases caused decreasing stresses. Changes in the gob modulus followed a reverse trend. Changes in seam height followed a similar trend as that of the rock mass and coal. The 8-ft seam increased pillar stress, and the 4-ft seam decreased pillar stress. Changing modulus and seam height values in one seam and not the other also had little effect on MS. For all model runs, the change in MS for all interburdens, moduli, and seam heights was less than 2 pct.

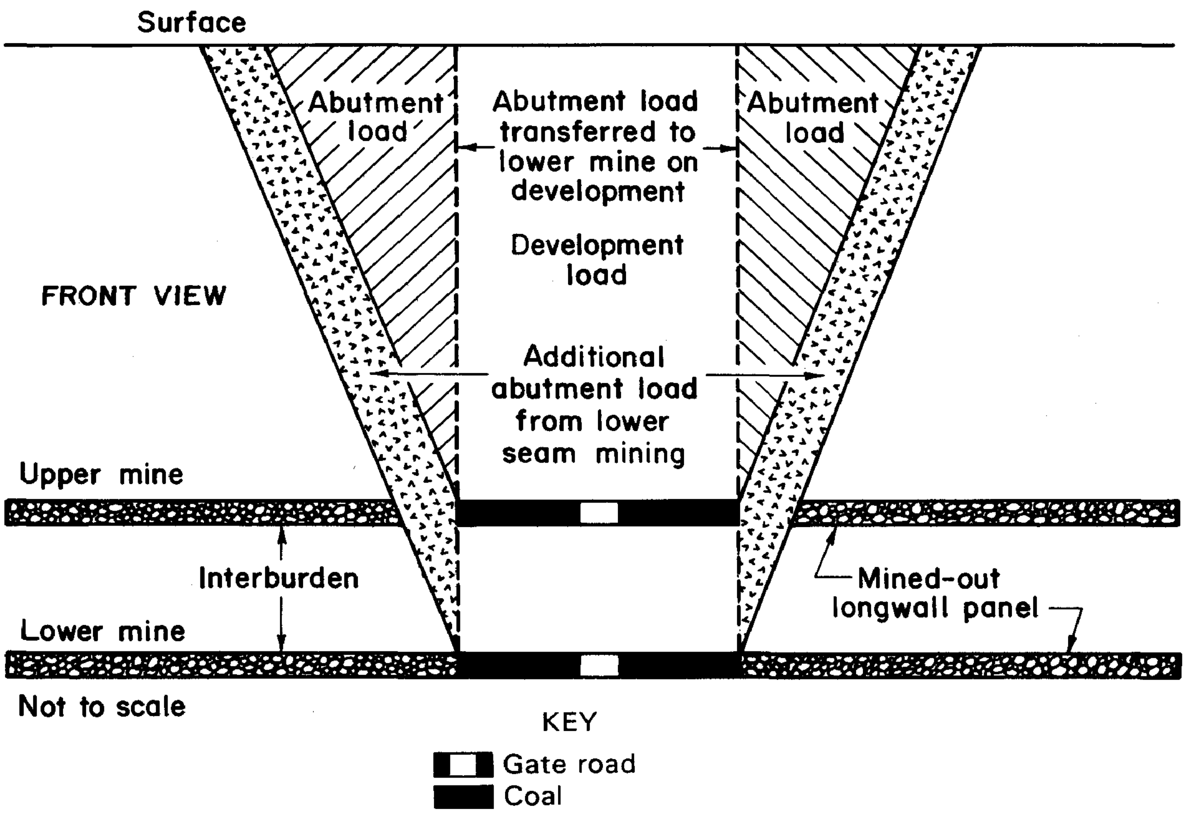

Figure 7.—Abutment from upper mine transferred to lower mine gate roads at isolated load.

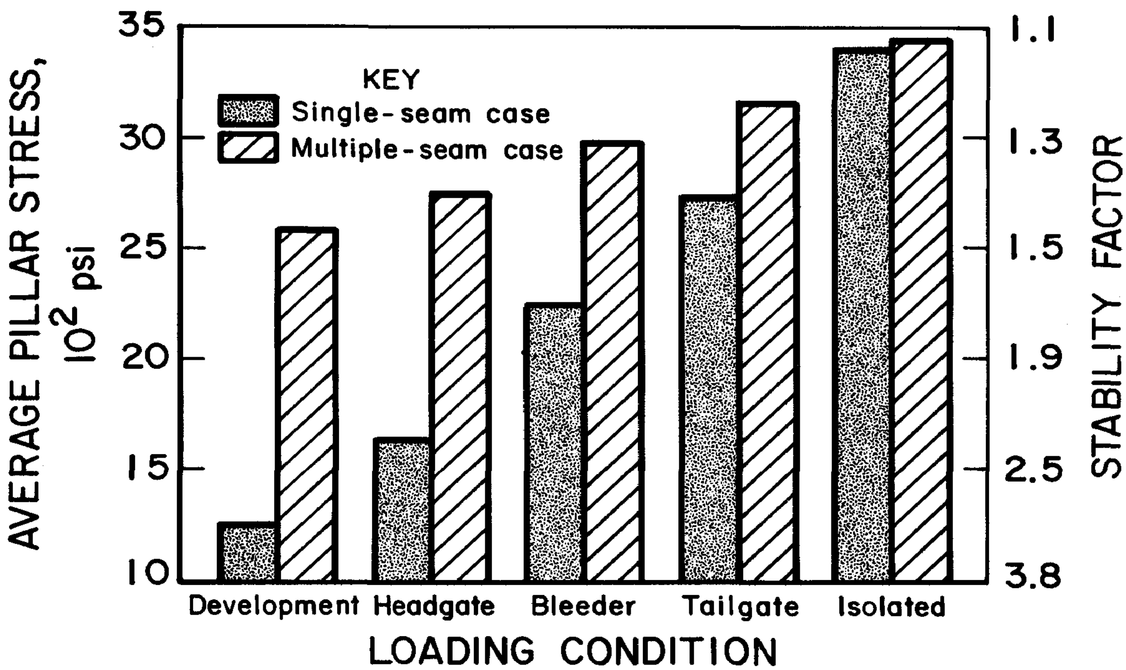

Figure 8.—Average pillar stress and stability factors for multiple-seam and single-seam case at each stress condition.

SUMMARY

The purpose of this report is to provide mine operators with guidelines for determining safe pillar designs for multiple-seam mining situations. Because of the high degree of geologic and mechanical property variability experienced in coal and coal measure rocks, proof of a mathematical model's accuracy for mine design is not as easily determined as in other engineering disciplines. However, since very little information exists to help mine operators design pillars for multiple-seam applications, the use of a model makes available a tool from which the initial design process may begin.

The mathematical model used in this report was calibrated by the design method ALPS, which uses empirical data obtained from single-seam longwall mine operations. Although the model is based on ALPS, which has been very successful at determining gate road pillar stability in single seams, the results obtained from the use of this model have not been compared with actual in-mine multiple-seam situations. Therefore, to add validity to the model's results, an investigation will be conducted to verify that mines with superimposed longwall gate roads follow the trends predicted by the model. If discrepancies are evident, it may be necessary to modify the model's input parameters to refine the results. This does not mean that the MS's generated by the model cannot be used without confidence. It does mean, however, that one should be cognizant of the fact that this model, as well as all mathematical models, should be viewed as a tool to solve problems. Therefore, these guidelines should not be used without site-specific experience and sound mining judgment.

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