EXTRACTION RATIO IN THIN SEAMS ASSURING NO SURFACE SUBSIDENCE[1]

by

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Abstract. The depletion of thicker coal reserves has resulted in thinner seams becoming economically attractive. Surface protection against subsidence limits the extraction ratio to 50% for the room and pillar method as a "no subsidence condition". That rule was developed for pillars with smaller width/height ratio because seams mined at the time were commonly 6 feet thick. Over time pillar ribs deteriorate around the pillar perimeter and thus decrease the area of the pillar. Using 50% extraction as the no subsidence condition in the squat pillar category (below 42 in with w/h > 7) causes unnecessary losses of reserves because squat pillars are stronger. In this paper a method is presented for the design of long-term pillars. Based on the analysis of pillar deterioration and field observations, an increase of the "no subsidence" extraction rate to 60% for squat pillars is proposed.

Introduction

The present rate of depletion of the economic coal reserves is a cause of concern for government agencies overseeing the coal mining industry. Actually conservation of reserves through proper utilization is an obligation according to 405 KAR 18:010, General provisions, Section 2 Coal Recovery: " *Underground mining activities shall be conducted so as to maximize the utilization and conservation of the coal, while utilizing the best appropriate technology currently available to maintain environmental integrity, so that reaffecting the land in the future through surface coal operations is minimized*".

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The permitting rules concerning subsidence issues have been formulated based on results of research and practical experience gathered in the past.. At that time thicker seams were mined, thus it is reasonable to question whether rules developed for thicker seams can be extrapolated to the low seams. The observations support the view that it leads to the over conservative design of pillars causing unnecessary loses of reserves.

Limiting the extraction ratio to 50% as a means to prevent surface subsidence has been established in Pennsylvania, where modern coal mining was first practiced at a large scale. This principle has been adopted by other coal mining states, Kentucky included. The remaining coal reserves of Eastern Kentucky and neighboring states mainly in thin coal seams and under higher overburden, which require pillars with width/height ratio exceeding 5. This fact, together with the low mining height puts them into the "squat pillar" category.

Overview of the subject

One of the oldest and most fundamental of the mining sciences is design of pillars which constitute the primary support for the overburden. Pillar failures continue to occur despite more than 100 years of research and experience, threatening mining operations, and causing strata movements in the overburden that may eventually reach the surface in the form of

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subsidence. The ratio of overburden depth to the mining height is considered in the analysis of surface subsidence. Numerous pillar design formulas have been developed, based upon laboratory testing, back-analysis of mine case histories, and full-scale pillar testing.

A squat pillar is defined as a mine pillar with the width much larger than its height. The width to height ratio has major influence on pillar strength. It has been proven through theoretical analysis, model works, and observation in mines that the squat pillar's bearing load capacity is high. The basic concept of squat pillar design for overburden support is that failure conditions in the pillar are limited to the perimeter zone around the pillar, while the core remains intact. The distressed material provides a horizontal, confining stress. Failure of a pillar perimeter, when excessive, cannot be tolerated because it creates unsafe conditions for the mine. These include rib rolling, and increased span of the excavation, which negatively affects roof stability. Concepts of excavation stability and pillar stability need to be discussed. The first one is essential for safety of mining operations while the second is responsible for surface protection against subsidence. The design objectives of mine pillars, which are required to fulfil the particular requirements stated above, separately or jointly determine pillar sizes. Within the short period of time such as required for mining of coal, excavation stability, if assured, automatically fulfills the requirement for pillar stability. However, when looking for long-term pillar stability, where the objective is surface protection against subsidence, deteriorating pillars over long periods of time may not be large enough, even though they served satisfactorily for stability of the excavation during active mining operations.

Subsidence related characterization of the Kentucky mining field and its remaining reserves

Coal deposits exist in two regions of Kentucky as the Eastern and West Kentucky coal fields. Their geologic, mining and physiographic conditions differ considerably. Eastern Kentucky coal is higher quality and because of that mining of thin seams is economically acceptable. Since the subject of this study is related to subsidence in reference to squat pillars, which typically are designed in thin seams, only the Eastern Kentucky coal field will be characterized to the extent meaningful for the subjects being discussed.

Mining in the Eastern Kentucky coal field has been active since the beginning of the last century and over that period of time most of the reserves in thicker seams have been depleted. Consequently, the prevailing parts of the remaining reserves are within the 28 to 42-inch category of seam thickness. It is anticipated that the majority of future mining will be in low seams where the mining height will be 35 to 42 inches. Because of the requirements of clearance, the 28-inch coal seams will be cut higher to 35 inches, by either taking rock from the roof or mine floor. The seams where, according to Kentucky Geological Survey, larger reserves still exist are the Amburghy, Elkhorn 3 (Lower), Fire Clay and Hazard No. 4. The reserves in those seams are estimated to be around 16 billion tons.

Geomechanical properties of the rock layers encountered in coal mine pillars

Ranges of coal strength

The calculation of pillar stability takes into account the external load, which can be based on tributary area or the height of pressure arch, and the in situ coal strength. A study conducted by NIOSH in the United States concluded that uniaxial compressive strength tests on small coal samples do not correlate with in-situ pillar strength (Mark and Barton, 1996). That study, as well as South African and Australian studies, has found that using a constant seam strength of 6.2 Mpa (900 PSI) works well for empirical pillar design.

The subject of pillar strength remains controversial. The 900 PSI number seems to be rather a mean value which can be either too high or too low depending on seam conditions. Although it has little effect on pillar strength as a structural element, it certainly can affect the behavior of a coal rib in a mine. If a good characterization of geotechnical conditions and a reliable testing program have been carried out, realistic strength values can be established for the coal seam and a decisive stability factor can be identified.

Characteristics of parting strata in coal pillars

Partings are common in coal seams. From the standpoint of parting strength, three cases can be distinguished. The first case is when the parting is stronger than coal, being composed of sandstone, siltstone or hard shale. The second case is, when parting strength is close to that of the surrounding coal, and the third is when parting is weaker than coal. This together with several possible partings in a seam creates numerous possibilities, making impractical any generalization. *However, when analyzing subsidence implications only, one case is significant, that is when a parting of considerable thickness is weaker than coal,*

and thus decreases the pillar strength. The above statement requires additional explanation. Some partings are composed of weak material such as moist fire clay, and they are actually squeezed out from the rib of a coal pillar. The other partings can be actually stronger than coal during excavation development, but through exposure to the ambient mine atmosphere and its seasonal fluctuation in moisture, they quickly weather with a substantial decrease of their mechanical properties. A similar situation exists with the mine floor, which can be either weaker than coal or become weaker when its moisture content increases. Since the interest of this study is in the long-term effect on pillar stability, it is assumed that the processes detrimental for strength have taken place. *Then, in both cases of weak parting and weak mine floor, their thickness is a governing factor when considering related deterioration of pillars.* Based on the authors' experience, it is proposed that 4-inch thick weak parting is significant for the increased deterioration of the coal pillar. In the present stage of research only the parting issue will be addressed. Since in low mining conditions seams with thicker parting are not mined for economic reasons, the maximum parting thickness considered in this study is 9 inches.

Mine pillars in low seams

Definition of a squat pillar

It is generally accepted that the probability of pillar failure and loss of strength decreases for pillars with large width to height (w/h) ratios and becomes negligible. The higher values of w/h factor cause increase of lateral confinement towards the center of the pillar, increasing pillar strength. The larger the w/h ratio, the greater the confinement developed in the pillar. In strong sandstone surrounding strata, high strengths are obtained in pillars with w/h = 5, but in pillar systems with weak strata surrounding the coal, larger w/h for pillars are required to develop a similar high load-carrying capacity. Therefore a squat pillar can be defined as a pillar that has a high load-carrying capacity, and depending on the strata surrounding the coal *a pillar can be considered squat at w/h > 7.* The Madden squat pillar formula (13) is applicable to pillars with the width-to-height ratio equal to or larger than 5. Therefore, assuming the angle of internal friction of coal is 37.5°, the angle of internal friction of parting is 20°, the mining height is3.5ft, and the parting thickness is 0.25ft, the pillar width, W, was found which fulfills the requirement

$5 = (W - 2\,x_b)/h$

With $x_b = x_1 + x_2$

Where x_1, x_2 = penetration of yielding zone in the coal or in the parting (found using the angle of internal friction.

Note: $x_1 = x_2$ because the pillar is considered to be symmetrically loaded

$5 = (W - (2*1.7778))/3.5$

The pillar width found is W = 21 ft, and the width-to-height ratio for this pillar is initially R = 6 (development conditions). Another qualifying factor of a squat pillar is the height of the pillar itself. *Height of 42 inches is considered the upper limit of the squat pillar category.* For a pillar of that height and for the minimum pillar width of 25 feet allowed by MSHA, the w/h factor is 25/3.5=7.14

Recommended calculation of pillar strength using Bieniawski's formula with modification for changes in pillars over time

Since no directly applicable reference could be found in the technical literature, the authors propose their own approach, which is based on observations of squat pillars in the mines. Old mine works were selected for mine visits. The observations and results of surveys conducted were used as the basis for the approach presented below.

The essence of the proposed system of pillar strength calculation is that in an old pillar its bearing surface area is reduced through over-stressing and the weathering process of a rib around the pillar perimeter. Two cases will be considered: first, seams without parting, and second, a seam with parting. In pillars with parting the most unfavorable case will be considered assuming a parting located close to the bottom of a seam. In this case the volumetric size reduction is the largest, even thought the width of the deteriorated zone does not increase when compared with another position of a parting.

The reduction of pillar area is assumed to be related to the angle of internal friction of the seam components (coal and parting). The deterioration process is caused by the stress concentration around the pillar perimeter, which eventually reaches the strength of the material. This is especially critical since this is the zone exposed to weathering processes, which weaken coal and parting in a coal seam. As the result of this process the initially vertical solid rib of a pillar becomes slope-like with an angle of 45+φ degrees, where φ is the angle of internal friction of a rib rock (coal or parting). Similar processes take place in nature, where for certain types of rock there is a certain stable

slope, as can be observed in mountains and river canyons.

It is proposed that the pillar strength calculations will be made using the Bieniawski system, but based on a smaller pillar area without the perimeter zone, the width of which is found through the above determination system. Two cases will be considered.

In the first case - it is assumed that no parting is present in the pillar, thus only a coal angle of internal friction is taken into account, resulting in a corresponding decrease of bearing area of the pillar

In the second case - it is assumed that the parting is at a lower portion of the seam, which results in the least favorable conditions. Soft parting such as fireclay, after deterioration, alters to a soil-like material that has a low angle of internal friction, around 15-20 degrees. The resulting pillar rib line is as depicted in Fig1. When compared with the first case the width of a perimeter zone around the pillar increases accordingly, further decreasing the bearing area of the pillar.

Comparisons have been made among the results of back calculations using the proposed modified Bieniawski formula, and also the Wilson and Madden formulae. Wilson's approach assumes that the conditions of pillar perimeter change in response to over-stressing as a result of abutment pressures. His interest was in design principles for the yield pillar, which is intentionally "made soft" and thus deformable. The approach presented here assumes that the pillar perimeter becomes weak as a result of weathering and time-dependent deterioration. Nevertheless, the outcome of both approaches is similar and a useful comparison of both methods can be made.

Analysis of long-term stability for squat pillars

Pillars in underground coal mines deteriorate over time. The following types of structural deterioration are noticed on older pillars:

1. Spalling of the coal rib;

2. Squeezing of softer parting layers by the top and bottom portion of the coal;

3. Conversion of a mudstone/claystone layer to clay caused by prolonged exposure to mine moisture;

4. Separation of coal and parting along slick interfaces;

5. Peeling of parting layer.

The rate of pillar deterioration is a function of mining height and time. Vander Merve (1998) found that there is good correlation between mining height and pillar life. The higher the pillar, the greater the scaling, but the scaling decelerates with time. Scaling of pillar sides can also be considered as a mode of pillar failure.

Field observations

The actual mine observations and the findings derived from them were used for validation of the concept of pillar deterioration. Field trips were made to several Eastern Kentucky mines operating in low seams. At certain locations in those active mines there are pillars ranging from 20 to 70 years old. Pillars within each area have been measured, photographed, and results of the observations were used for validation of the design approach proposed in the paper. Out of five mines, Altec mine conditions were worse than those found in other case studies. Therefore, the Altec mine observations were used to evaluate the qualitative and quantitative pillar deterioration mechanism described in the paper, to prove that the proposed method is sufficiently conservative. The other mines were mining the Amburghy seam - pillars over 20 years old, Hazard No. 4 seam - pillars are 60 years old, Harlan seam – pillars that were 40 -50 years old, and Pond Creek seam - pillars that were35- 45 years old. The Alma seam in the Altrec mine is 45 inches thick. Five sites in the mine were closely examined. The overburden cover was highest over Site 2 and Site 5. Pillars in one row at Site 2 were only 20 feet wide, while at Site 5 the minimum pillar dimension was 50 feet. Since the 20-foot wide pillars at Site 2 are smaller than 25 feet, which is presently allowed by regulations, data from Site 5 were used, where the development width of pillars was 50 feet, and the overburden thickness is 1050 feet. The observed rib scaling was measured at 2 feet and 4 inches. The opening was designed to the original entry width of 18 feet, 7 inches. The measurements taken during the site visit indicated that the present opening width is 20 feet, 11 inches.

Calculation of yield zone penetration using the Wilson 1972 formula.

The following formulae will be used for the calculations:

$$k = (1 + \sin\rho)/ (1 - \sin\rho) \qquad (1)$$

Where k is a constant employed in soil mechanics and ρ is the angle of internal friction of the coal

$$F = (k-1)/ (\sqrt{k}) + \{(k-1)^2/ k\} * \tan^{-1}(\sqrt{k}) \quad (2)$$

$$x_b = (h/F)\ln (q/p) \tag{3}$$

Where x_b = width of the crushed core, h = extracted height, F = constant, q = overburden stress, H = overburden depth

$$\sigma_{av} = 4k/FR^2\{q\,[R - (2/F)(\ln(q/p)-1)]\} -p(R+2/F) +((kq+\sigma_c)/R^2)[R-(2/F)\ln(q/p)]^2 \tag{4}$$

Proposed calculation of yield zone penetration based on the angle of internal friction of coal and the presence of parting (Bieniawski formula).

The following formula will be used for calculations:

1. Calculate the pillar strength using Bieniawski's formula (Bieniawski 1992):

$$S_p = S_1 (0.64 + 0.36W/h) \tag{5}$$

Where S_p = pillar strength
  S_1 = in situ seam strength
and h = seam height.

2. Calculate the vertical load on the pillar (pillar load) using the tributary area method:

$$S_v = \gamma H\,(W+W_e)(L+W_e)/(WL) \tag{6}$$

Where S_v = pillar load,
γ = unit weight of the overburden,
  H = depth of the seam,
  W = pillar width (minimum pillar dimension),
  L = pillar length (maximum pillar dimension),
and W_e = entry width.
For square pillars, the equation (6) is:

$$S_v = \gamma H\,((\,W+W_e)/W)^2 \tag{7}$$

The pillar load can be expressed in terms of extraction ratio:
$$S_v = \gamma H/(1-e) \tag{8}$$

$$e = (A - A_p)/A = 1 - (A_p/A) \tag{9}$$

Where e = extraction ratio
  A = whole area of mining
  A_p = portion of A that is occupied by pillars.
3. Calculate the pillar stability factor (SF) as

$$SF = Pillarstrength/Pillarstress = S_p/S_v \tag{10}$$

4. According to Madden (1991), (the squat pillar formula, for pillars with a W/h > 5 is

$$S_p = kV^a\,R_0^b\{b/\varepsilon[(R/R_0)^\varepsilon-1]+1\} \tag{11}$$

Where k = in-situ strength of the coal, R = width-to-height ratio, R_0 = lower limit of W/h at which a pillar is considered squat, ε = Rate of increase in strength, V = pillar volume. Substituting k = 7.2 Mpa, a = - 0.0667, b = 0.5933, R_0 = 5.0, and ε = 2.5 (All of the assumed values are taken from Salamon and Wagner (1985) study of South African coal mines and are in S I units.)

$$S_p = 0.0786/V^{0.0667}\{R^{2.5} + 181.6\} \tag{12}$$

The formula 12 can be simplified for a quick calculation:
$$S_p = 0.0786(W^{2.366}/h^{2.5667}) + 9. \tag{13}$$

Justification of the application of the tributary area theory.

The pressure arch conceives that load is transferred across an opening (or several openings) of limited width by a "pressure arch" that forms in the strata. The minimum value of the maximum width of this pressure arch is a function of the depth of the bed and is given by the formula:

$$W = 3(H/20 + 20) \tag{14}$$
Where: W = width in feet of minimum value of the maximum width, H = overburden depth.
For the Atlec mine W = 217.5ft. The width of the mined area (Site 5) is 237.5 ft; therefore, the tributary area theory can be used at the limit.

Following is a Key for the table 2.:
Column 1: pillar width *   Column 2: entry width *
Column3: $\varphi/2+45^0$ Rib ang   Column 4: extraction ratio *
  φ:angle of internal
  friction of coal
Column 5: parting thickness   Column 6: mining height
Column 7: w/h   Column 8: yield zone   **
Column 9: pillar **   Column10: pillar strength**
core
Column 11: pillar stress **   Column12: safety factor**
* on development
** after pillar perimeter deteriorates – long – term condition.

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Tab 1. Calculation of admissible pillar stress by Wilson formula
overburden depth 1050ft, no parting considered, Altec mine.

$\rho(°)$	H(ft)	w(ft)	h(ft)	σ_c	k	F	q(psi)	x_b(ft)	R	σ_{av}(psi)
25	1050	50	3.75	3500	2.464	1.805	1155	9.0918	13.333	2700.238
30	1050	50	3.75	3500	3	2.551	1155	6.4348	13.333	3962.752
35	1050	50	3.75	3500	3.69	3.54	1155	4.6374	13.333	5257.488
40	1050	50	3.75	3500	4.599	4.873	1155	3.3684	13.333	6690.86
45	1050	50	3.75	3500	5.828	6.712	1155	2.4455	13.333	8408.468
50	1050	50	3.75	3500	7.549	9.324	1155	1.7605	13.333	10627.24

Tab 2. Calculation of pillar strength using Bieniawski's formula.
the yield zone is based on the angle of internal friction,
overburden depth 1050ft, Altec mine.

1	2	3	4	5	6	7	8	9	10	11	12
W(ft)	B(ft)	$\rho(°)$	e(%)	P(ft)	h(ft)	R	$X_{b(ft)}$	w(ft)	Sp(psi)	S_v(psi)	SF
50	18.7	57.5	47.03	0.17	3.75	13.33	2.4	45.2	4477.54	2668.20	1.68
50	18.7	60	47.03	0.17	3.75	13.33	2.19	45.62	4513.79	2619.30	1.72
50	18.7	62.5	47.03	0.17	3.75	13.33	1.98	46.04	4550.05	2571.73	1.77
50	18.7	65	47.03	0.17	3.75	13.33	1.79	46.42	4582.86	2529.79	1.81
50	18.7	67.5	47.03	0.17	3.75	13.33	1.6	46.8	4615.66	2488.88	1.85
50	18.7	70	47.03	0.17	3.75	13.33	1.42	47.16	4646.74	2451.03	1.90

Calculation of yield zone based on angle of internal friction of coal and parting.

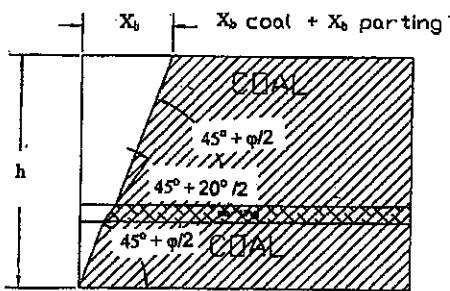Note: The angle of internal friction of coal is in the range of $25°$ to $50°$ (Fig. 1)

Fig. 1 Concept of yield zone penetration based on angle
of internal friction of coal and presence
of parting

The yield zone penetration based on the angle of internal friction confirms the measurements made at the Altec mine. The calculated yield zone penetration of 2.4 feet matches the observed one for the rib angle of 57.5 degrees. The corresponding safety factor for the pillar is 1.68 and the mine observations proved that the pillar is stable. The above calculations do not take into account confinement provided at the bottom of the pillar by the fallen material (which was observed in the mine).

Comparison between Madden's formula and Bieniawski's formula

Safety factors have been calculated for the mining geometry and conditions at Site 5, Altec case study, using the short version of the Madden (13) and the Bieniawski formula.(Fig2) The pillar load for both calculation systems assumed reduced pillar size due to the development of a yield zone x_b (column 8). The width of the yield zone depends on rib angle ρ (column 3).

To evaluate the influence of the w/h factor on results of calculations using both methods, a comparison was made using conditions at the Altec mine assuming 25-by- 25 foot pillars and seam thickness of 3.75 feet resulting in w/h factor equal to 6.67 (Fig. 2). It can be seen that comparing the pillar strength, both formulae give nearly identical results. The difference in values increases slightly for larger values of rib angle, meaning a smaller yield zone. One has to note that this is the case when the w/h factor is equal to 13.33. (Fig. 3)
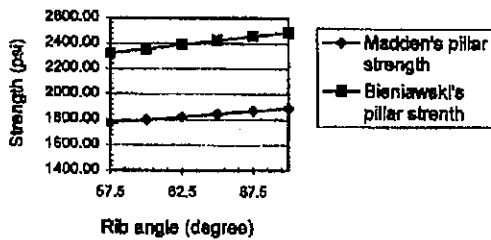
Fig. 2 Comparison between Madden's pillar strength
and Bieniawski's pillar strength for pillar with
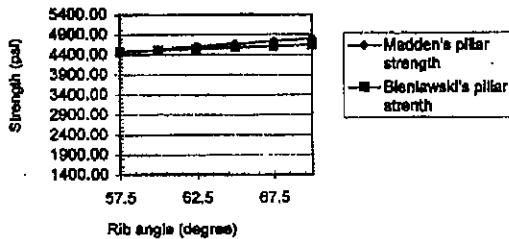width - to - height ratio equal 6.67

Fig. 3 Comparison between Madden's pillar strength
and Bieniawski's pillar strength for pillar with
width - to - height ratio equal to 13.33.

Bieniawski's pillar strength is larger than
Madden's pillar strength at small width-to-height ratio.
Madden underestimates the pillar strength at small
width to height ratio. With increasing width-to-height
ratio, Madden's pillar strength becomes higher than
Bieniawski's pillar strength, but the difference is not
significant.

Results of calculations in reference to the observations
in mines.

The method proposed by the authors utilizing
the Bieniawski formula gives values, which correspond
well with mine observations in the worst conditions
encountered. This proves that the proposed approach is
realistic and sufficiently conservative to be used for
prediction of long-term stability of squat pillars.

The proposed limit of extraction ratio for no subsidence
effect to replace the 50% rule presently applied to squat
pillars.

In the analysis previously presented it has
been demonstrated that the long- term stability of pillars

is related to loss of internal friction related to strength
of coal and also to the thickness of weak parting, if such
is found in the seam. In thicker seams where higher
productivity can be achieved, it is possible to mine coal
economically with a thick parting. In some mines the in
– seam reject can be as high as 60 %. The author has
actual experience with mine cases in Eastern Kentucky
where the thickness of weak parting was exceeding 2
feet. However, in the squat pillar category, where the
mining height is below 3.5 ft, it will not be economical
to mine seams with more than 0.75 ft of parting.
Therefore, the influence of weak parting (of limited
thickness) in thin seams is potentially smaller than in
conditions with higher mining heights where thicker
partings are tolerable. This had additional implications
for emphasizing the qualitative difference between
long-term behavior of "normal" and "squat" pillars, and
the resulting (long-term) extraction ratio. A numerical
example is given to validate the above statement.

Numerical example

The assumed mining conditions are: mining
height is 3 feet, pillar width is 47.5 ft, and entries are 20
feet wide, thus driven on 67.5 ft centers. It is assumed
that pillars have a strength of 900psi. The extraction
ratio for this geometry
$e = 1-(Ap/A) = 1- (2256.25/4556.25) = 0.5048$, thus
roughly equal 50%. Assume the same geometry but a
mining height of 6 feet. If the angle of internal friction
of coal $\varphi=40$ degree (a mid range of φ), rib angle is 65
degree. The long-term deterioration will reduce the
width of 3 feet high pillar (3 x tan25) x2 = 2.798 ft.
Thus the reduced pillar width will be 47.5-2.798 =
44.70 ft.
For the 6-ft high pillar, the reduction of width is (6x tan
25) x 2=5.595 ft, resulting in the final dimension of
41.9 ft.
The reduced area of the taller pillar is $(47.5^2) - (41.9^2) =$
500.28 sq.ft, while for the 3-ft pillar it is 258.16 sq.ft.
500.28/258.16 x 100 = 193.8%. The reduced area for
squat pillar is thus 51.2% less when compared to the 6-
ft. high pillar.
In terms of the extraction ratio (calculated for the
reduced pillar sizes)
-     for the 3 ft high pillar $e = 1- (1998.09/67.5^2) =$
1-0.4385= 56%
-     for the 6 ft high pillar $e = 1 -(1755.61/67.5^2) =$
1-0.38 = 62%
As it can be seen that the increase of the actual
extraction ratio for the 6-ft. high pillar is about twice as
much as the increase for the 3-ft. pillar.
This is to be expected because the reduced area is
proportional to the rib height of the pillar. In the
example presented here, by increasing pillar height

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100% (to 6 ft), the reduction of pillar size was double when compared to the 3-ft. high pillar.

The pillar strength can be calculated using the Bieniawski formula for both heights from the example above. A USBM (Mark) default in situ coal strength of 900 PSI will be used.

For the 3-ft pillar height $Sp = 900(0.64 + 0.36 * 47.5/3) = 5706$ PSI

For 6-ft pillar height $Sp = 900(0.64 + 0.36*47.5/6) = 3141$ PSI

The increase of pillar strength between the 3 and 6-ft pillar heights of the same dimensions is $5706-3141 = 2565$ PSI which represent $2565/3141*100 = 81.7\%$

If the squat pillar 3-ft in height is designed for approximately 60% extraction ratio, its width is 34 ft. Checking the extraction ratio $e = 1 - (34^2/54^2) = 60.36\%$

The long-term reduction of pillar width is 2.798 ft, thus the pillar will be 31.2 ft wide. Recalculated extraction ratio for this reduced pillar size is:

$$e = 1 - (31.2^2/54^2) = 66.7\%$$

The 50% extraction limit for no subsidence conditions has been developed in Pennsylvania at the time when seems which were mined remained above 6 ft. in height. The rule of 50% extraction ratio for no surface subsidence conditions was established more through experience than through any analysis. It held true and because of its simplicity was adopted in the surrounding mining states throughout the Appalachian coal fields. That rule has been set for extraction ratio and related pillar sizes as they are cut during the development. In the technical literature no reference was found which would address directly the subject discussed in this paper.

Based on the presented analysis and field observations which support the findings, *it is recommended that for the squat pillars, the "no subsidence effect extraction ratio" will be allowed to increase to 60%.* This seems justified since it was demonstrated that there was much less reduction in pillar size (51.2%) and much higher strength (81.7%) for the squat pillar studied compared to a 6-foot high pillar.
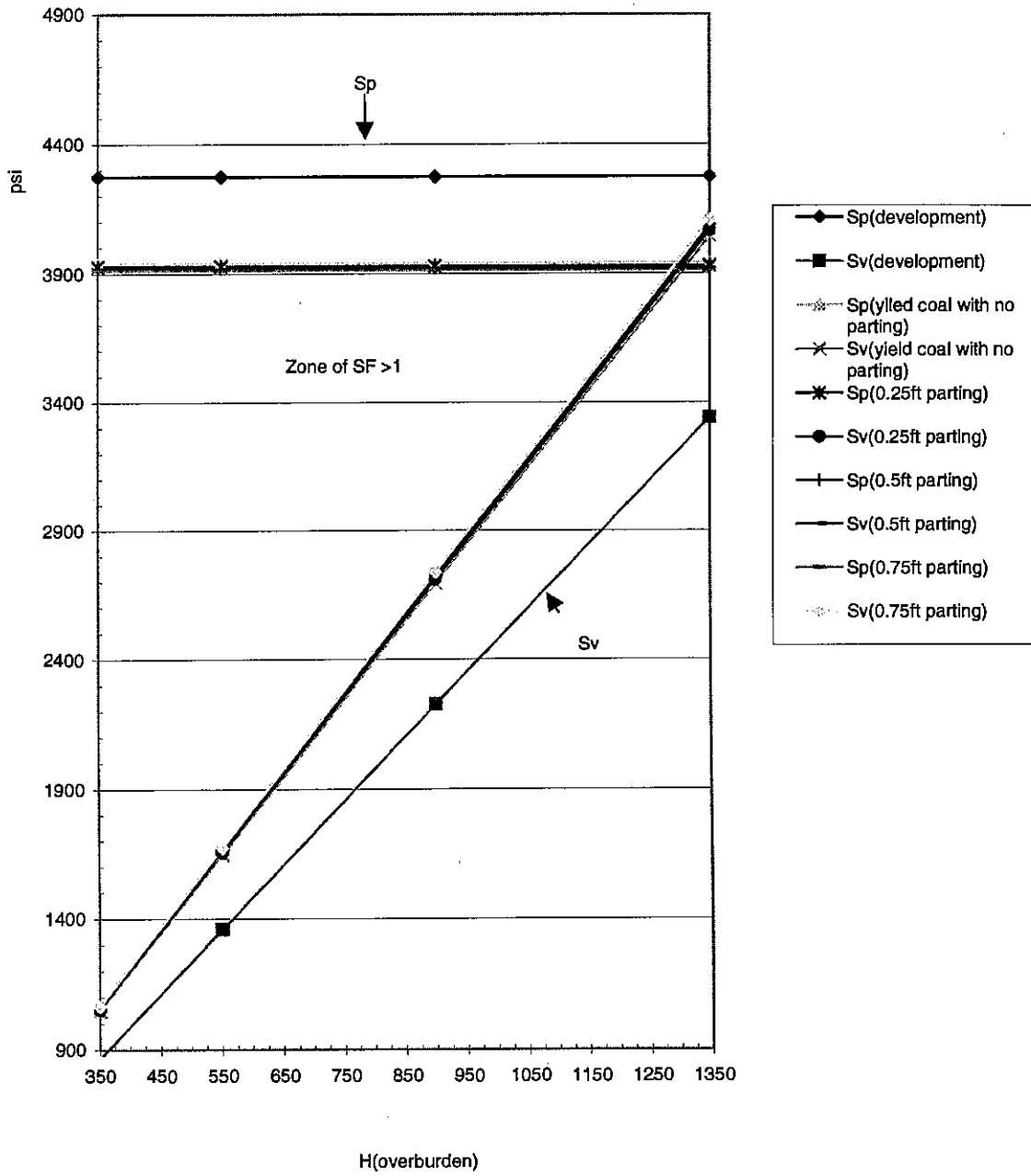
Summary and recommendations

It is proposed that for pillars within the squat category (less that 3.5 ft), the "no subsidence extraction ratio" will be increased to 60%. An example of design charts (1, and 2) is given to demonstrate how they can be used for evaluation of particular mining conditions in terms of appropriate pillar sizes and safety factors in reference to the overburden thickness. The present study has not addressed the soft floor conditions, which in certain mining situations can have strong influence on pillar performance. This subject will be addressed in planed further research, so that the system of evaluation of subsidence potential over squat pillars could cover the full range of the possible conditions.

Acknowledgement

Chart 1. Range of use of pillar 40ft, mining height 3.5ft entry width 20ft, and coal $\varphi=35°$, rib $\rho= 62.5°$

Legend:
- Sp(development)
- Sv(development)
- Sp(ylled coal with no parting)
- Sv(yield coal with no parting)
- Sp(0.25ft parting)
- Sv(0.25ft parting)
- Sp(0.5ft parting)
- Sv(0.5ft parting)
- Sp(0.75ft parting)
- Sv(0.75ft parting)

Y-axis: psi — values 900, 1400, 1900, 2400, 2900, 3400, 3900, 4400, 4900

X-axis: H(overburden) — values 350, 450, 550, 650, 750, 850, 950, 1050, 1150, 1250, 1350

Sp

Zone of SF >1

Sv

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