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Critical Dimension Concept in Pillar Stability

T.Ünlü
Department of Mining Engineering, Zonguldak Karaelmas University, Zonguldak, Turkey

ABSTRACT: This paper is based on a study carried out to investigate the stability and dimensioning of coal pillars at various depths. Critical dimensions for coal pillars are discussed. The results of the study show that the minimum width for small and/or yielding coal pillars should not be less than 10 metres. In the case of soft roof and/or especially soft floor strata conditions, special attention should be given to pillars with width-to-height ratios (W/H) between 4 and 10. Pillar strength increases as the pillar width is increased, depending on the geomechanical characteristics of the coal seam. However, after a certain W/H value, th^trength of a coal pillar increases rapidly and it is almost impossible to yield the pillar completely.

1 INTRODUCTION

Pillar design and stability are two of the most complicated and extensive problems in rock mechanics and strata control. Although these problems have been investigated for a long time, to date only a limited understanding of the subject has been gained. Empirical pillar strength formulas together with the tributary area concept have been used to design pillars for room-and-pillar mining systems at relatively shallow depths (< 300 m). Although these pillar formulas do not give accurate results, they have often been found to be satisfactory for general design at shallow depths. At shallower depths (i.e., 100 - 300 m), pillars are subjected to considerably lower stresses, which make it easier to apply various mining methods. Despite the generation of horizontal stresses, which could assist in confining pillars in some situations, in general, the major constraint to pillar design at great depth is the high vertical stresses due to overburden depth. This is particularly relevant to deep coal mining because of the weak nature of the coal and coal-bearing strata. As the mining activities go deeper (> 300 m), these pillar equations suggest very large pillars since they consider only a limited number of factors related to the strength of coal pillars (i.e., size and shape effects). However, there are some other important factors related to the strength of coal pillars. These factors are depicted in Figure 1.

What are the critical dimensions for coal pillars? In order to comprehend the problem and therefore to seek a solution, the following questions must be addressed and reasonable answers should be sought concerning pillar loading and stability.

- How much load is imposed on a pillar and how is it distributed over a single pillar or row of coal pillars?
- What are the most important factors involved in the strength of the coal pillars under scrutiny?
- What İs the role of pillar confinement offered by the roof and floor strata in pillar stability?
- The final question: what type of formula or design criterion is the most appropriate for designing pillars in coal mining applications?

Before seeking answers to these questions, in order to understand the mechanical behaviour of coal pillars, İt İs important to classify them according to their stability.

2 CLASSIFICATION OF PILLARS

Pillars may be classified according to their functions underground, for example, as support pillars, protective pillars and control pillars. These descriptions, however, do not give any useful information about the stability of these pillars. Therefore, it becomes necessary to establish an alternative pillar classification system to distinguish pillars according to their stability and according to the possible failure zones İnside pillars (Figure 2). These are as follows:

- Abutment pillar (stiff pillar).
- Critical pillar (semi-stiff pillar).
- Yielding pillar.

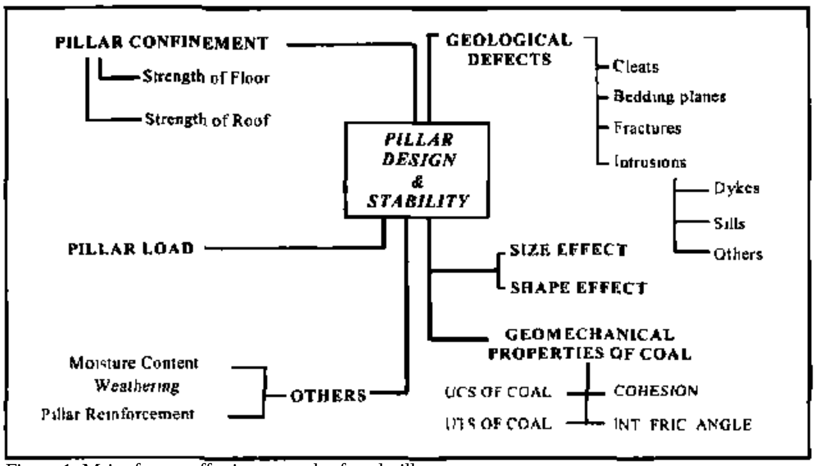

Figure 1. Major factors affecting strength of coal pillars.

2.1 *Abutment pillar*

This type of pillar is capable of supporting development loads and additional transferred loads during the service life of working areas without yielding or transferring any significant part of the load. They need a sufficient width of unyielded core so that stresses are smoothly dissipated into the floor without creating any adverse effects (i.e., preventing floor failure). These types of pillars are the essential backbones of the entire mine support system.

2.2 *Critical pillar*

This type of pillar is characterised by a failure mode which occurs where roof and particularly floor conditions are unfavourable. The mechanism is as follows: an insufficient width of elastic core remains during pillar loading, and this elastic core transfers highly concentrated stresses into floor strata, causing them to yield. As a result, yielding of the floor initiates beneath the pillar and gradually develops towards the roadway, which suffers from a considerable amount of floor heave and convergence. Similar observations have been made during mining practices (Carr et al., 1984, 1985; Koehler et al., 1996). The critical pillar size should be avoided at all costs by either widening or narrowing the pillar. This case is similar to the footing problem in soil mechanics.

2.3 *Yielding pillar*

A stable yielding pillar can be defined as a pillar which can sustain some part of the load being imposed on it and transfer any excess load without losing its overall integrity and residual load-bearing capacity. It is not necessary that these pillars should always have small dimensions, but they are generally designed to be narrow to maximise coal recovery. *Any* yielding pillar may lose its integrity during loading and/or by spalling from the ribs, thus gradually reducing its original dimensions. Under such conditions, a stable yielding pillar can become an unstable yielding pillar and can rapidly and completely collapse. To avoid this, side meshing in conjunction with nb or cable bolting should be considered.

3 PILLAR DESIGN EQUATIONS

Many formulas of average ultimate pillar strength that have been proposed take into account two important factors. Most of these formulas can be grouped into two categories:

$$\sigma_p = \sigma_c \left[a + b\left(\frac{W}{H}\right)\right] \rightarrow \text{ The linear form} \qquad (1)$$

$$\sigma_p = K \cdot \frac{W^{\alpha}}{H^{\beta}} \qquad \rightarrow \text{ The power forai} \qquad (2)$$

where-

Cp = pillar strength,

o_c = uniaxial compressive strength of a cubic coal sample of the critical specimen size,

a, b = dimensionless constants usually chosen so that a+b=l,(Table2)

K = represents numerically the strength of coal, (Table 1),

a, ß = dimensionless constants expressing the shape effect (Table 2), and

W, H = pillar width and height, respectively.

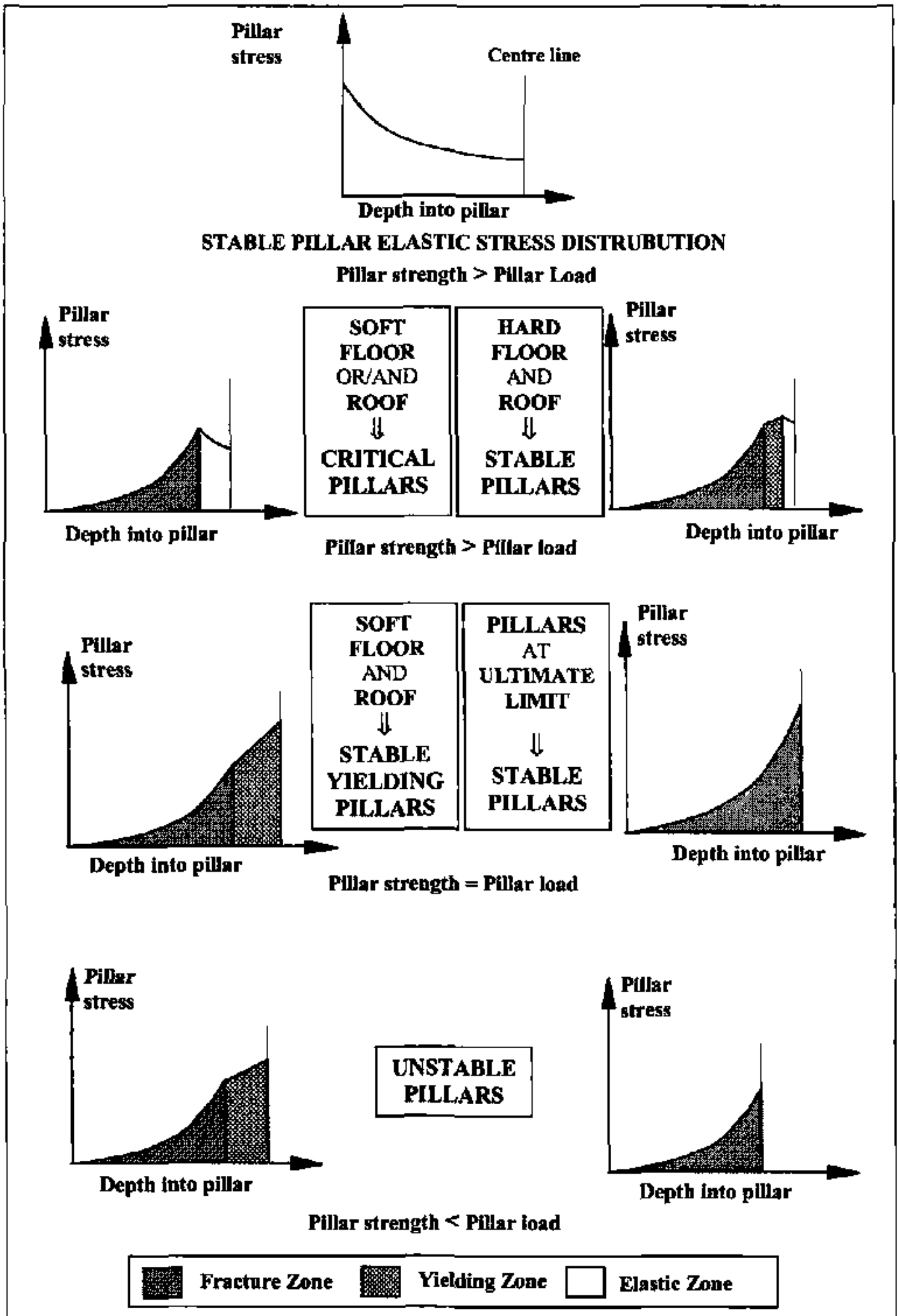

Figure 2 Possible failure zones developed inside pillars

Table 1. Values of K used inequation 2 (Farmer, 1985).

Researchers)	K (MPa)	Comments
Greenwatd et al. (1939)	19.3	Orig. in psi for W, H values in inches (ABD)
Salamon - Munro (1967)	9.1	Orig. in psi for W, H values in feel (S.Africa)
Bieniawski (1968)	6.9	Orig. in psi for W, H values in feet (S.Africa)
Jenkins - Szeki (1964)	12.4	Originally in psi for W, H values in feet (S.Africa)
Wagner (1974)	11.0	W, H values in metres. In-situ tests (S.Africa)

Table 2. Constants used in equations 1 and 2 (Farmer, 1985).

Researcher(s)	a	b	α	β	Comments
Bunting (1911)	0.7	0.3	-	-	Laboratory
Obert, Windles and Duvall (1946)	0.78	0.22	-	-	Laboratory
Bieniawski (1968)	0.64	0.36	-	-	In-situ, S. Africa
Van Heerden (1974)	0.70	0.30	-	-	In-situ, S. Africa
Wang, Skelley and Wolgamott (1977)	0.78	0.22	-	-	In-situ, USA
Sorensen and Pariseau (1978)	0.69	0.31	-	-	Statistical, USA
Greenwald, Howarth and Hartman (1939)	-	-	0.5	0.83	Statistical, USA
Streat (1954)	-	-	0.5	1	Statistical, S. Africa
Holland (1964)	-	-	0.5	1	Statistical, USA
Salamon - Munro (1967)	-	-	0.46	0.66	Statistical, S. Africa
Bieniawski (1968)	-	-	0.16	0.55	Statistical, S. Africa
Morrison, Corlett and Rice (1975)	-	-	0.5	0.5	In-situ, Canada

Aldiough rectangular pillars as well as square pillars have been widely used in underground coal mining, there are only a few formulas available for designing rectangular pillars (Salamon & Oravecz, 1976; Wagner, 1980; Peng, 1986; Mark, 1996).

All of the empirical pillar strength formulas were developed particularly for room-and-pillar mining at relatively shallow depths. Hence, they are most suitable for pillars in a particular coal region and for small W/H ratios (i.e., up to 4). However, weak roof or floor conditions and/or weak bands in coal seams are particularly important because they may cause the pillar to yield in tension radier than compression. Babcock (1981, 1985) conducted a series of experiments on model pillars, using concrete, coal and rock, and he concluded that the end constraint, not width-to-height ratio, is a significant variable in determining the pillar strength. Moreover, the failure mechanism of a large (squat) coal pillar is different from that of a coal sample tested in the laboratory. This is because the constraint offered by the yielded region to intact core will not build in small coal samples and small coal pillars. As a result, empirical pillar strength formulas are not recommended for coal pillars wiüi width-to-height ratios (W/H) of ten or more as they underestimate pillar strength due to the fact that most of them were derived from laboratory and/or in-situ tests conducted on prismatic coal samples up to 2 m in width.

Mark & Barton (1996) state that the size effect is related to the coal structure. Significant strength reduction due to increased specimen size is only valid for blocky coals. Tests conducted on small-size friable coal samples can be used to predict the uniaxial compressive strength of the coal mass itself.

3 INVESTIGATIONS OF CRITICAL PILLAR DIMENSIONS

3.1 *General*

The first step in pillar design is to calculate the pillar stress due to overburden load and transfer loads as a result of roadway development and coal extraction operations in longwall panels. The second step İs to calculate the pillar strength, which is more difficult than calculating pillar loads. The strength of slender pillars (W/H<4) can be predicted more easily than those of intermediate (4<W/H<10) and large coal pillars (W/H>10), because die failure mechanism of these pillars is roughly similar to laboratory-scale pillar specimens (up to 2 m) and the uniaxial compressive strength of slender pillars can be predicted more accurately. Therefore, pillar strength equations derived from the results of these investigations may be used for slender pillars at shallow depths with a reasonable degree of accuracy. The strength of large pillars, however, cannot be determined easily. This is because of the confinement built up through the centre of the pillar, depending upon the intensity of vertical stress and the geomechanical characteristics of the coal pillar.

3.2 *Critical dimensions of pillars in room-and-pillar mining*

Two main pillar design approaches have been suggested and widely accepted for designing pillars in room-and-pillar and/or longwall mining. The first one is Wilson's Confined Coal Concept (Wilson, 1980) and the second one is Barron's approach (Barron, 1982, 1992). Both of these approaches

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consider some of the important parameters affecting pillar stability, such as confinement developing from the sidewalls to the centre of coal pillars. Although these two approaches seem to have similar features, there are significant differences regarding the post failure characteristics assumed for the coal seam.

In order to determine the strength of coal pillars with various geomechanical properties, a Windows-based computer program which was developed to design pillars in underground mining systems was used to estimate pillar strength taking into account various parameters related to the strength of coal. The program mainly uses Barron's approach, but with several modifications. Some of the input parameters used in Pil-Sta are shown in Figure 3 (Ünlü, 1994).

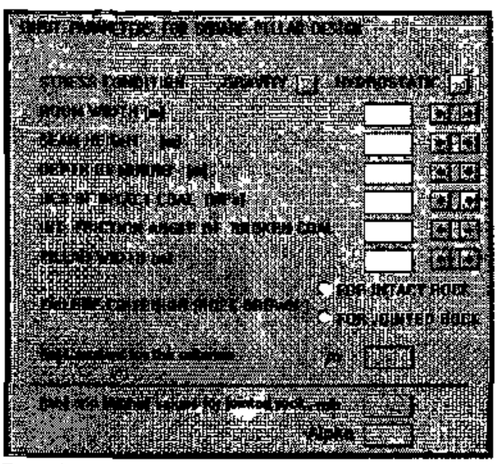


Figure 3 Input parameters used in Pil-Sta

The critical dimension is the minimum width of a pillar that can maintain stability without transferring loads by losing its integrity and load-carrying capacity at a certain depth. This dimension is affected by not only the vertical stress intensity increasing with depth, but also the geometric and geomechanical characteristics of coal pillars and the roof and floor strata.

The results show that the most important factors in pillar strength are the pillar width and the geomechanical characteristics of the coal seam. Width-to-height ratio also plays an important role (Figure 4). After a certain pillar width, there is a small change in required pillar width since the strength of the coal pillar increases dramatically (Figure 5).

Figure 5 and Figure 6 also show that after a certain pillar width, the pillar strength develops rapidly and tends to go to infinity. However, the geomechanical characteristics of roof and floor strata and the magnitude of secondary stress distribution around roadways surrounding coal pillars are more important in terms of the stability of underground openings. Physical and numerical modelling studies conducted on gateroad stability in deep mining conditions have shown that while squat pillars remain stable, gateroads suffer from a considerable degree of side spalling and convergence (Figure 7a). Moreover, intermediate-size pillars (W/H=7.5) designed in relatively soft floor conditions show a considerable degree of floor heave and buckling-type strata failure (Figure 7b) (Whittaker, 1993; Ünlü, 1994).

3.2 *Critical dimensions of pillars in longwall mining*

As previously mentioned, at shallower depths, pillars are subjected to considerably lower stresses. This makes it easier to apply various mining methods. Despite the generation of horizontal stresses which could assist İn confining pillars in some situations, in general, the major constraint to pillar design at great depth is the high vertical stresses due to overburden thickness. This is particularly relevant to deep coal mining because of the weak nature of the coal and coal-bearing strata. Transfer loads from neighbouring faces should also be taken into account.

Some design approaches and/or pillar strength equations suggest very large pillars (e.g., 100 m or more). This is irrelevant because the author believes that total disintegration of a pillar is not expected if the pillar width-to-height ratio is 10 or more. If only this condition is satisfied, i.e., the pillar width-to-height ratio is 10 or more but the ultimate load limit is exceeded, catastrophic pillar failure would not be expected. However, because of the high stresses due to depth, instability problems in gateroads such as roof and/or floor failure may be encountered.

In order to examine pillars in longwall mining and to determine reasonable pillar dimensions for longwall pillars wim various gateroad layouts, the Pillar Stability (Pil-Sta) program was used. The results show that pillars less than 50 metres in width are satisfactory in all cases without transferring loads to neighbouring panels (Figure 8). If pillars are designed with less than this dimension, they can still resist loads without losing their integrity. However, additional support should be introduced to gateroads to maintain the stability of these openings.

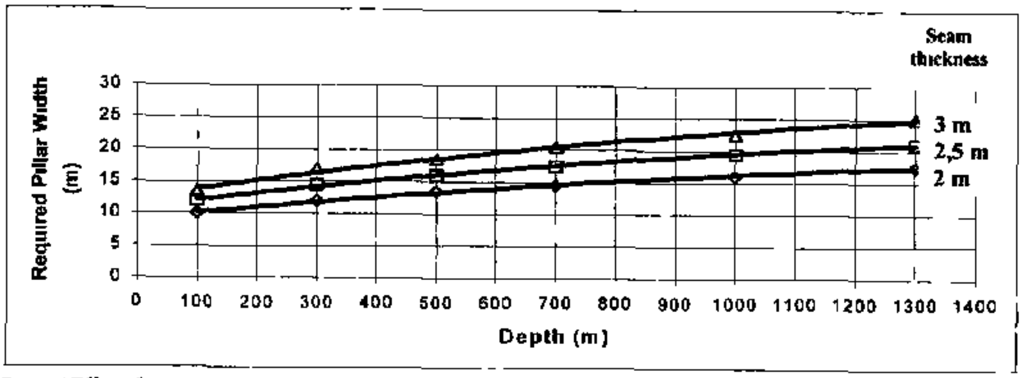


Figure 4 Effect of seam thickness on required pillar width for room and pillar coal mining

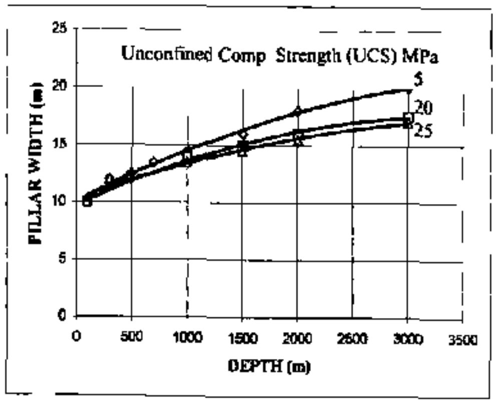


Figure 5 Effect of UCS of coal on pillar width

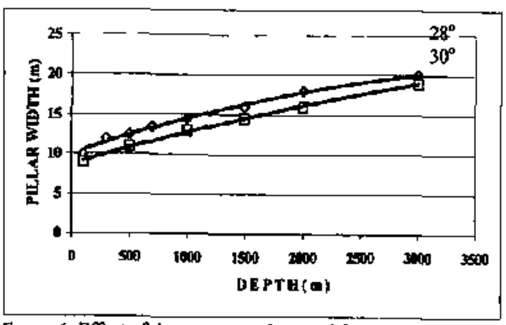
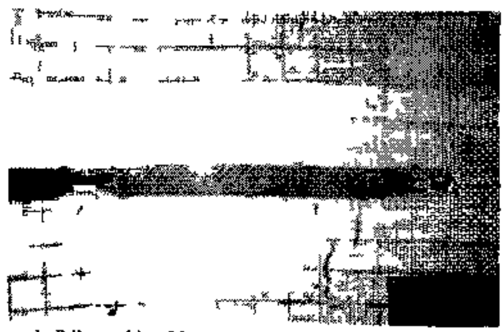


Figure 6 Effect of the variation of internal friction angle of coal on pillar width

a Pillar width – 15 m



b Pillar width – 20 m

Figure 7 Physical modelling results

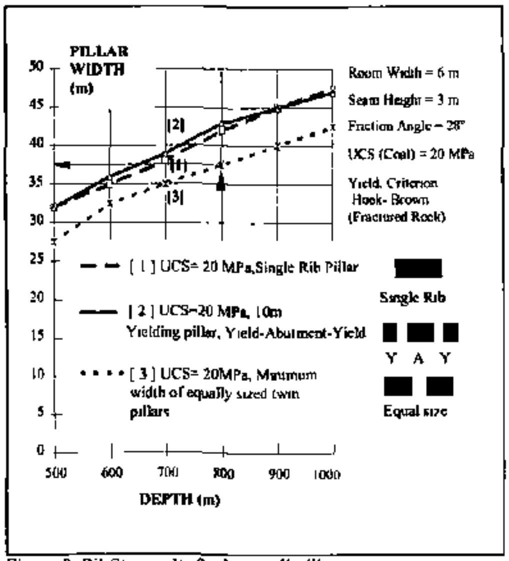


Figure 8. Pil-Sta results for longwall pillars.

As can be seen in Figure 9, increasing the width of small pillar (Y) from 10 to 15 m results in only a small change in terms of required abutment pillar (A) width for the same depth. It is also important that the design engineer be careful not to design critical pillars. Therefore, designing "one yielding + one squat" pillars is better than designing "two equal pillars" or "one intermediate + one squat" pillars.

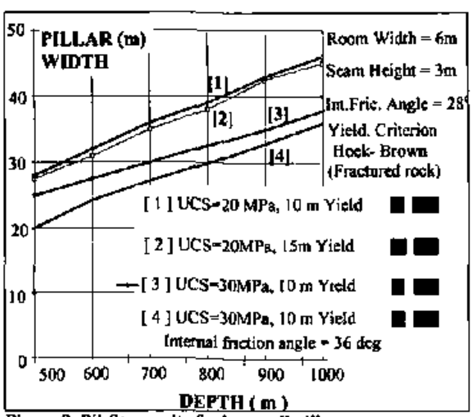


Figure 9. Pil-Sta results for longwall pillars.

4 CONCLUSIONS

The minimum width for small and/or yielding coal pillars should not be less than 10 metres. Any stable smalî pillar may lose its integrity and residual load-carrying capacity, depending upon the other environmental factors.

Special attention should be given to pillars with width-to-height ratios between 4 and 10, if soft roof and/or especially floor strata conditions exist. These pillars may lead to excessive roof sagging and floor heave.

After a certain pillar width, which is affected by the geomechanical characteristics of the coal seam and coal-bearing strata, the strength of coal pillars increases rapidly, and it is almost impossible to yield pillars completely. However, the stability of roadways and surrounding openings becomes much more important than the stability of the pillars themselves. Some of the pillar strength equations or design approaches suggesting very large pillars (more than 40-50 m) for deep coal mines should not be used.

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