

Full Length Research Paper

Chronological development in coal pillar design for bord and pillar workings: A critical appraisal

M. Jawed^{1*}, R. K. Sinha² and S. Sengupta³

¹Department of Mining Engineering and Chairman, JEE-ISM, Indian School of Mines, Dhanbad-826004, Jharkhand, India.

²Indian School of Mines, Dhanbad, India.

³National Institute of Rock Mechanics, India.

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In this study, proper design of coal pillar has ever remained a difficult and challenging task because of two conflicting objectives, namely the conservation of coal on one hand that requires coal pillars to be of minimum size and stability of pillars, and on the other hand that ensures safety of working. The complex loading conditions, the occurrence of seams in close succession and geological abnormalities present in seams make the design problems of coal even more complex and complicated. An attempt has been made in this paper to enlist and describe briefly factors affecting pillar strength and empirical strength equations/formulae developed by different researchers in different parts around the globe. Further, a comparative study has been made for a given set of geo-mining conditions to know the suitability of these equations in terms of their being either over-estimators or under-estimators.

Key words: Pillar strength, coal pillar design, pillar strength.

INTRODUCTION

Bord and pillar method of mining coal seam involves driving two sets of parallel in-seam headings, one set being orthogonal to another, thereby forming square or rectangular pillars. These pillars are subsequently extracted allowing the overlying strata to cave in the decoaled area. In some cases where circumstances so demand, decoaled area is packed with incombustible material to avoid caving of the roof in order to keep the surface intact and free from any subsidence.

The design of coal pillars remains one of the most difficult tasks because of two conflicting requirements to be fulfilled. On one hand, the size of the pillar should be as small as possible to enable maximum recovery of coal, while on the other hand, the pillar should be large enough to support the load of overlying strata. The design problem complicates further due to the interaction of multiple factors such as complex loading conditions, natural variation within the coal seam, influence of contiguous seam workings, geological abnormalities etc.

Like design of any other structure, the design procedure of coal pillars in bord and pillar mines essentially consists of knowing precisely the strength of coal pillar, the load on the pillar (cover weight) and linking the two with a desirable factor of safety. Researchers in different countries have developed empirical relations for estimation of strength of coal pillars for the geo-mining conditions of the coal mines in their own countries. Thus, the empirical relation developed for a particular set of conditions will not be precisely applicable to another set of conditions existing in other country. This paper, therefore, seeks to present a critical review of pillar design by different researchers around the globe.

FACTORS AFFECTING THE PILLAR STRENGTH

Pillar strength is a function of a host of factors, the most significant being depth of seam from the surface, height of working, thickness of seam, dip of the seam, width of galleries, strength of coal, strength of roof and floor rocks, geological abnormalities in the seam (fold, fault, presence of band etc.), presence of water and weathering underground, proposed layout such as partial extraction

*Corresponding author. E-mail: profmjawed@yahoo.com.
Tel./Fax: +91 326 2296628.

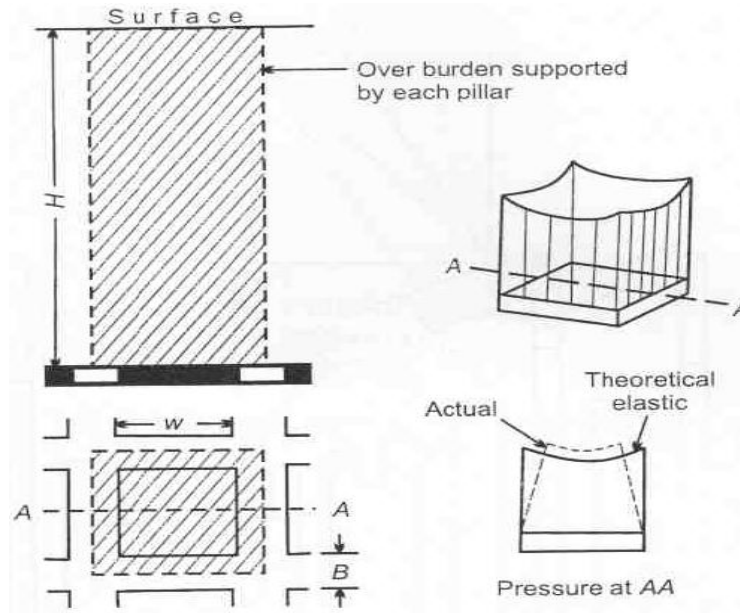


Figure 1. Pillar load according to tributary area theory in a wide array.

or full extraction, uniaxial and triaxial strength of coal, width-to-height ratio of pillar, shape of pillar (square or rectangular), pre-excavation horizontal stresses, condition of roof-pillar and floor-pillar contacts, method of gallery drivage (blasting or road header/continuous miner) etc.

PILLAR LOAD

The load on pillars comprises of the vertical virgin stress (in level or near level coal seams) and the stress induced by the excavations around pillars. For inclined seams, the virgin horizontal stress must also be considered.

Pillar arrays in level seams

On a regular array consisting pillars of a more or less uniform shape and size, the vertical virgin stress is taken equal to the cover weight of the strata in normal coal measures. However, in geologically disturbed areas, *in situ* stress measurement results should be used. Figure 1 shows the block of overlying rocks each pillar has to support. The average rock pressure “P” over the pillar is simply the weight of this block divided by the pillar area. For square pillar

$$P = \gamma H \left(\frac{W+B}{W} \right)^2 \quad (1)$$

For rectangular pillar

$$P = \gamma H \frac{(W+B)(L+B)}{WL} \quad (2)$$

Where, H is the depth of the seam, W is the width of pillar, L is the length of pillar and B is the bord width. These equations work very well in practice for regular arrays provided the width of the panel is at least equal to the depth of cover. If it is less, the pillar load may be less. The most commonly accepted pressure distribution over a pillar in an infinitely wide uniform pillar array is shown in Figure 1 the average being given by Equations 1 and 2 for square and rectangular pillar, respectively.

In an irregular pillar arrays or for panels whose width is less than the depth of cover (H), the load is overestimated for small pillars by tributary area theory and underestimated for large pillars. Under hard sandstones, the over and underestimation in irregular arrays will be further magnified and over a narrow pillar panel, the pillar load will be further reduced. In such situation, it is best to adopt numerical methods, the displacement discontinuity method being probably the most convenient (Sheorey, 2006).

Pillar arrays in inclined seams

The rock pressure normal to inclined seam pillar arrays is given by Trumbachev and Melnikov (1964) as:

$$P = \gamma H \left(\frac{W+B}{W} \right)^2 \cdot (\cos^2 \alpha + K \sin^2 \alpha) \quad (3)$$

Where α is the angle of inclination of the seam with the

horizontal, and K is the ratio of horizontal to vertical stresses.

Coal pillar strength equations developed by different researchers under different conditions

The journey of pillar design method started with the consideration of scale effects of the laboratory size specimens to extrapolate for the actual size of mine pillars. This included the testing of rock at laboratory scale. Subsequently, the design got modified with large scale *in situ* tests. Wagner (1974) brought a paradigm shift in the design of pillars by introducing the core confinement concept. This was later on advanced by Das (1986) using the concept of squat pillars (pillars having a width to height ratio greater than 4 to 6).

Pillar strength concept by Bunting

The science of pillar design can be traced back to Coulomb in 1773 (Mark, 2006). However, the first scientific approach to pillar design for coal mines can be attributed to Bunting (1911). Bunting carried out exhaustive tests on various sizes of cubes (2 to 6 inches size) and prisms (2.25 to 12.25 inches high) of anthracite. The results of tests were tabulated with reference to the size of specimens and the ratio of height to lateral dimension. They demonstrated that the coal prisms followed some law of strength relative to their height and breadth. Based on this laboratory experiments, they conducted back-analysis of full-scale pillar failures underground.

Using the same approach as followed by Bunting, a number of pillar design equations were developed around the globe for the next seven-decades. During this period, many researchers had recognized that the pillar strength is influenced significantly by the width to height ratio. This research on size effect dragged for a sufficiently longer duration.

Pillar strength equation by Zern Edward Nathan

Zern (1928) edition of his book titled "Coal Miner's Pocketbook" gave the following equation for the strength of coal pillars:

$$C_p = C_1 \sqrt{\left(\frac{w_p}{h_p}\right)} \quad (4)$$

Where, C_p is the pillar strength, C_1 is the coal strength parameter = 4.8 to 7.0 MPa (700 to 1000 psi) w_p is the pillar width and h_p is the pillar height.

Pillar strength equation by Greenwald

Greenwald et al. (1941) considered *in situ* tests on slender pillars of size 30 cm and gave the strength of pillar as:

$$C_p = 0.67k \frac{\sqrt{w_p}}{h_p^{0.53}} \quad (5)$$

Where, C_p is the pillar strength, k is the strength of unit cube of coal sample, w_p is the pillar width and h_p is the pillar height. This equation was developed on a limited number of 7 samples with low correlation coefficient, thus inefficient.

Pillar strength equation by Holland and Gaddy

Gaddy (1956) used coal samples of various cube sizes from five different seams. He tried to establish relation between laboratory specimen strength and strength of actual pillar. Gaddy was of the opinion that the strength decreases with increasing size of specimens which he expressed as follows:

$$k_G = S_c / \sqrt{d_G} \quad (6)$$

Where, k_G is the Gaddy constant [estimated strength of a 2.5 cm (1 inch) cube], S_c is the strength of coal specimen and d_G is the dimension of the specimen in inch.

His work (Holland and Gaddy, 1964) became popular as 'Holland-Gaddy Pillar Strength Equation' as given as follows:

$$C_p = k_G \frac{\sqrt{w_p}}{h_p} \quad (7)$$

Where, C_p is the pillar strength, w_p is the pillar width and h_p is the pillar height. The strength equation is applicable to slender pillars.

Coal mines regulation versus pillar size

In India, the dimensions of the pillars are regulated by Regulation 99(4) of Coal Mines Regulation 1957 (CMR, 1957). The regulation stipulates that the width of galleries shall not exceed 4.8 m and height of galleries shall not exceed 3 m. For different width of galleries varying from 3 to 4.8 m and for different depth of working, the Regulation stipulates the minimum dimension of pillars.

Pillar strength equation by Salamon and Munro

Salamon and Munro (1967) carried out an intensive investigation into the strength of coal pillars by analyzing

statistically 96 intact and 27 collapsed pillar geometries from South African coal mines. The following empirical relation developed for strength of pillar became quite popular.

$$C_p = k_{SM} h_p^\alpha w_p^\beta \quad (8)$$

Where, C_p is the pillar strength, $k_{SM} = 7.176$ kPa, h_p is the pillar height, w_p is the pillar width, $\alpha = -0.66$ and $\beta = 0.46$.

The main reason for the popularity of Salamon and Munro (1967) equation was that the data was used from the mines and the strength was taken as the mean strength of coal pillars as opposed to the strength of coal specimens. The strength equation is applicable to slender pillars. For evaluation of long-term stability of Indian coal pillars, Sheorey et al. (1986) generalized the Salamon and Munro (1967) equation as $C_p = 0.79k w_p^{0.46} / h_p^{0.66}$

where k has to be evaluated by testing of specimens of size 30 cm.

Pillar strength equation by Obert and Duvall

Obert and Duvall (1967) developed empirical relation for the compressive strength of specimens having height-to-diameter (or width) ratio as 0.25 to 4.0.

$$C_{so} = C_{10} \left[0.778 + 0.222 \left(\frac{d}{h} \right) \right] \quad (9)$$

Where, C_{10} is the compressive strength of specimens having ratio of $\frac{d}{h} = 1$, C_{10} is the compressive strength of a specimen having $d/h = 1$, d is the diameter of the specimen and h is the height of the specimen.

They suggested that the compressive strength of a rib pillar in a massive elastic rock can be approximated by the use of Equation 9, provided d and h are replaced, respectively by w_p and h_p .

$$C_p = C_{10} \left[0.778 + 0.222 \left(\frac{w_p}{h_p} \right) \right] \quad (10)$$

Where, C_p is the compressive strength of the pillar, w_p is the width of pillar and h_p is the height of the pillar. The strength equation is applicable for slender pillars. They argued that the results based on above calculations would yield strength on a conservative side for the following reasons:

- The compressive strength of a specimen having cross sectional dimensions W and L normal to the applied load, with $W < L$, is stronger than a specimen with circular cross section of diameter W ,
- If the surfaces of pillar are concave, when formed by driving circular openings, the strength of such pillar would

be greater than that of a pillar with straight sides which is due to driving of rectangular openings.

- The end constraint on a pillar formed in a rock continuum would be greater than the end constraint normally employed in a standard compressive test, a factor that would increase the pillar strength to some extent.

Pillar strength equation by Cook

Cook et al. (1971) advocated for the use of yielding pillars between the barrier pillars for an improved extraction ratio of coal. For the design of yield pillars, the knowledge of complete stress strain curve of the pillar was a prerequisite. They utilized a stiff 100 MN jacking system for measuring the complete load-displacement curves of pillars with cross sections up to 2×2 m. The equation is given as follows:

$$C_p = \frac{71.8 w_p^{0.46}}{h_p^{0.66}} \quad (11)$$

Where, C_p is the strength of the pillar, w_p and h_p are the width and height of the pillars, respectively.

They concluded that a residual strength of only 1 bar for a crushed pillar is sufficient to provide roof support of 0.1 MN/m^2 of pillar cross section. They also observed that the average strength of the pillars was conforming to the Salamon and Munro (1967) relation. The stress versus compression curve at the center of the pillar had the highest peak indicating that the core of the pillar was quite strong.

Wagner approach to pillar design

Wagner (1974) also realized that, the center portion of a pillar was capable to withstand high stresses even when the pillar has been compressed beyond its maximum resistance or the strength of the pillar. Wagner (1974) observed that the failure commences at the circumference of the pillar and migrates towards the center of the pillar. At the time of overall structural failure of the pillar, the central position of the pillar had not reached its full load bearing potential. The strength of circumferential portion of a pillar was independent of the sample width to height ratio, whereas the strength of its center increases with increasing width to height ratio.

Wagner (1980) suggested that the Salamon and Munro (1967) equation was the result of a large number of case histories of failed and stable cases of South African bord and pillar mining which have been formed by drilling and blasting. Wagner (1980) considered the blasting damage on the skin of the coal pillar that reduced the pillar width up to 0.3 m. If the pillars are formed by cutting, say with continuous miners, the pillar strength will be more as the

skin damage does not occur. He quantified the benefits gained in terms of pillar strength and safety factor on account of using continuous miners as:

$$S = C_p(1 + \Delta w/w_0)^{2.46} \quad (12)$$

Where w_0 is the nominal pillar width and Δw is the effective increase in pillar width as a result of preserving the skin of the pillar.

Wilson's approach to pillar design

Wilson (1972b) carried out a mechanistic model of the pillar with a theoretical basis that could be applied to both slender and squat pillars. Later on, Wilson (1983) advanced his pillar equation for different conditions. Wilson's approach had a number of simplifying assumptions, important one being the assumption that the linear variation of the coal triaxial strength, however, practically it is observed to be nonlinear. The guiding principle for the development of Wilson's (1983) equation was that it could estimate vertical stress gradient within the yield zone, which was then integrated over the area of the pillar to arrive at the ultimate pillar resistance. The Wilson's equation with different cases in chronological order is enumerated below. All equations are in ton, feet units.

Wilson's (1972b) Equation

Case I: $[w_p > 2\bar{x}]$

For rectangular pillars

$$C_p = \frac{4\gamma H}{w_1 w_2} [w w_1 - 1.5(w + w_1)h_p H \times 10^{-3} + 3h_p^2 H^2 \times 10^{-6}] \quad (13)$$

For long pillars

$$C_p = \frac{4\gamma H}{w} (w - 1.5h_p H \times 10^{-3}) \quad (14)$$

Case II $[w_p < 2\bar{x}]$

For rectangular pillars

$$C_p = 667\gamma \frac{w}{w_1 H} \left[w_1 - \frac{w}{2} \right] \quad (15)$$

For long pillars

$$C_p = 667\gamma \frac{w}{h} \quad (16)$$

Where, C_p is the pillar strength, $\bar{x} = 0.0015 h_p H$ is the

failed coal zone in the pillar, $\gamma = 0.0707 \text{ t/ft}^3$ is the rock density, H is the depth of the coal seam from surface, w_p is the dimension of the square pillar and w and w_1 are the plan dimensions of the pillar.

Wilson's (1983) Equation

Case I: Stable roadways

$$C_p = \frac{1}{w w_1} \int_{qp}^{qH} (w - 2x)(w_1 - 2x) d\sigma + qp + \frac{\sigma_0}{w w_1} (w - 2\bar{x})(w_1 - 2\bar{x}) \quad (17)$$

Case II: Unstable roadways

$$C_p = \frac{1}{w w_1} \int_{qp}^{\sigma'} (w - 2x)(w_1 - 2x) d\sigma + qp, \text{ where}$$

$$\sigma' = qp \left(\frac{w}{h} + 1 \right)^{q-1} \text{ or } qp \exp \left(\frac{wF}{2H} \right) \quad (18)$$

Where, σ_0 is the in-situ strength, $p = 0.1 \text{ MPa}$ (a constant for broken coal), $q = 3.0$ (triaxial constant). Both Equations 17 and 18 are subject to two ground conditions as described below:

Condition a: Yield in roof, seam and floor

$$x = \frac{h}{2} \left[\left(\frac{\sigma}{qp} \right)^{1/(q-1)} - 1 \right] \text{ and } \bar{x} = \frac{h}{2} \left[\left(\frac{\gamma H}{p} \right)^{1/(q-1)} - 1 \right]$$

Condition b: Yield in seam, rigid roof and floor

$$x = \frac{h}{f} \ln \frac{\sigma}{qp} \quad \text{and} \quad \bar{x} = \frac{h}{f} \ln \frac{\gamma H}{p} \quad \text{where,}$$

$$F = \frac{q-1}{\sqrt{q}} + \frac{(q-1)^2}{q} \tan^{-1} \sqrt{q}$$

Bieniawski approach to pillar design

Bieniawski and Van (1975) based on his 8 years of *in situ* testing of 66 large coal specimens, up to 2 m in width and height and for width to height ratio ranging from 0.5 to 3.4, he gave the following empirical relation for pillar strength:

$$C_p = k_B \left[0.64 + 0.34 \left(\frac{w_p}{h_p} \right) \right] \quad (19)$$

Where, C_p is the Pillar strength (MPa), k_B is the unconfined compressive strength of a 30 cm cube pillar specimen (MPa), w_p is the pillar width and h_p is the pillar height.

Bieniawski (1968) had proposed originally that empirical constants of 0.556 and 0.444, instead of 0.64 and 0.34, respectively could be used to describe pillar strength. Logie and Matheson (1982) modified the Bieniawski (1968) equation to suit for squat pillars by introducing a power of 1.4 as follows:

$$C_p = k_B \left[0.64 + 0.34 \left(\frac{w_p}{h_p} \right) \right]^{1.4} \quad (20)$$

Pillar strength equation by Hustrulid

Hustrulid (1976) by this time had witnessed a number of equations all of which were unfolding the same phenomena. He came out with two predictive equations, namely the compressive strength-size relationship and the compressive strength- shape relationship which could be used to describe majority of experimental data very well.

Compressive strength-size relationship

$$\sigma_{cube} = \frac{k_H}{\sqrt{h_{prism}}} \quad \forall h_{prism} \leq 36 \text{ inches} \quad (21)$$

$$\sigma_{cube} = \frac{k_H}{\sqrt{36}} \quad \forall h_{prism} \geq 36 \text{ inches} \quad (22)$$

Compressive strength-shape relationship

$$\frac{\sigma_{prism}}{\sigma_{cube}} = 0.778 + 0.222 \frac{w_{prism}}{h_{prism}} \quad (23)$$

Where, σ_{cube} is the compressive strength of cube (psi), σ_{prism} is the compressive strength of prism (psi), k_H is the constant for each coal, w_{prism} is the width of the sample (inch), h_{prism} is height of the sample (inch).

Pillar strength equation by Pariseau

Pariseau (1982) presented the equation for the stresses acting on pillars in dipping seam that accounted for both the vertical and horizontal stress components. Equations 13 and 14 represent the normal and shear stresses respectively acting on inclined pillars. This is a variation of tributary area theory approach that takes into account both the components of in-situ stress viz. the vertical and horizontal components

$$\sigma_p = \frac{\gamma H \frac{(1+K_0)+(1-K_0)\cos 2\alpha}{2}}{(1-R)} \quad (24)$$

$$\tau_p = \frac{\gamma H \frac{(1-K_0)\sin 2\alpha}{2}}{(1-R)} \quad (25)$$

Where, σ_p is the average normal pillar stress (MPa), τ_p is the average shear pillar stress (MPa), γ is the unit weight of overburden (MN/m³), H is the depth below surface (m), K_0 is the ratio of in-situ horizontal to vertical stress, R is the extraction ratio, α is the dip of seam (degrees). The limitation to this theory is that, Pariseau (1982) assumed the magnitudes of horizontal stresses to be equal in horizontal plane. This is not the case as has been observed in field investigations.

Pillar equation by Agapito and Hardy

Agapito and Hardy (1982) conducted finite element analysis of pillars and proposed the following equation:

$$\frac{C_p}{K} = 1 + C \left(\frac{\sigma_h}{K} \right)^\alpha \quad (26)$$

Where, $\sigma_h = F_1 \sigma_{h1} + F_2 (\sigma_v - \sigma_{v1})$ is the average horizontal stress in the pillar, F_1 and F_2 are factors depending on pillar shape that are evaluated from the finite element analysis, the other two constants C and α were also evaluated from the finite element analysis, σ_{h1} is the pre mining horizontal stress, σ_v is the average vertical pillar stress, σ_{v1} is the pre mining vertical stress.

Pillar strength equation by Das

Das (1986) conducted tests on 6 types of Indian coal adopting a wider range of w/h ratio varying from 0.5 to 13.5. The tests were conducted on cylindrical specimens of NX size (54 mm diameter) with different heights at a constant strain rate of 10^{-3} s^{-1} in a 1.962 MN (200 tons) closed loop servo-controlled testing machine. It was observed that in general when the w/h ratio increases beyond 4-6, the post-failure characteristic starts ascending after an initial fall indicating a gain in strength (Figure 2). Das (1986) attributed this phenomenon for the reconsolidation of the broken coal mass. Stating that if the test is not conducted for long enough, the reconsolidation process may not be observed. At the w/h ratio of 13.5 the post-failure slope was throughout positive revealing a remarkable observation which indicates that if the pillars of such flatness are left in underground mines for support purposes they can retain

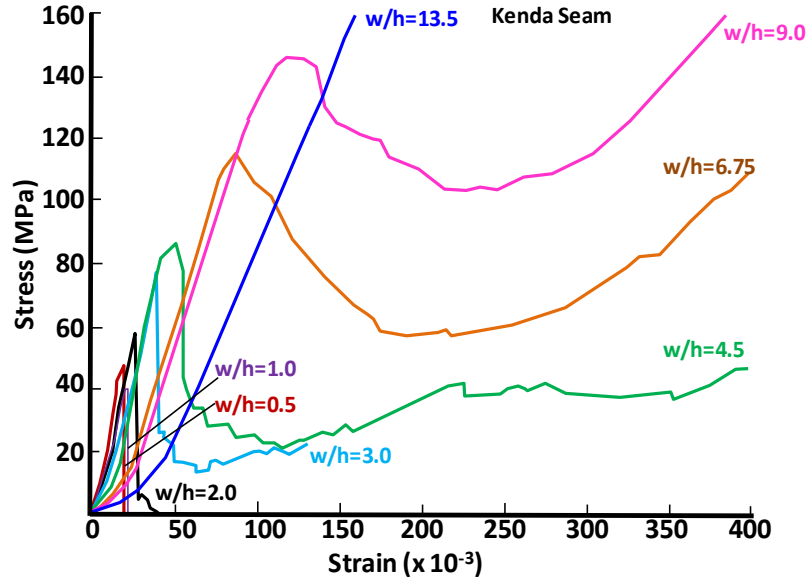


Figure 2. Influence of w/h ratio on the post-failure stress-strain behavior of coal 'calculated from the machine plot - without removing the effect of platen indentation' (modified after Das, 1986).

very high strength even after failure. At w/h ratios less than 4 to 6, the residual strength ultimately became zero which can be attributed to lower triaxial confinement at the specimen center. He also analyzed the post-failure modulus (maximum slope after strength failure) against the w/h ratio. The post-failure modulus observed to become zero around a w/h ratio of 10 and became positive with further increase in w/h ratio.

Pillar strength equation by Mark-Bieniawski

Mark et al. (1988), and Mark and Iannachione (1992) proposed new pillar strength equation which is widely known as the 'Mark-Bieniawski Pillar Strength Equation'. This equation was an improvement over the earlier pillar strength equation described by Bieniawski and Van (1975). Mechanistic approach to pillar design with stress distribution proposed by Wilson (1972a, 1983) could estimate vertical stress gradient within the yield zone, which could then be integrated over the area of the pillar to determine the ultimate pillar resistance. Bieniawski developed Equation 19 by testing square specimens and recognized that the equation underestimated the strength of rectangular pillars (Mark and Chase, 1997). Rectangular pillars and the effect of a pillar's length on its strength were examined and a modified version of equation, the Mark-Bieniawski Equation, was developed. It indicates that the strength of rectangular pillars exhibits a dependence on the width-to-height and width-to-length

ratios. The Mark-Bieniawski Equation is as follows (Mark and Chase, 1997):

$$C_p = S_1 \left[0.64 + \left(0.54 \frac{w_p}{h_p} - 0.18 \left(\frac{w_p^2}{h_p L_p} \right) \right) \right] \quad (27)$$

Where, S_1 is the *in situ* coal strength, assumed as 6.2 MPa, w_p is the pillar width, h_p is the pillar height, L_p is the pillar length. Thus, for Equation 27, as the w_p/h_p ratio increases so does the strength of the pillar. Additionally, as w_p/L_p increases the strength also increases. Equation 27 has been used successfully within the ARMPs computer program to design pillars for room and pillar mining.

Madden equation for squat pillars

Owing to the limitations of Salamon and Munro (1967) equation, which was statistically analyzed for pillars with width to height ratio of 3.6 or less, it proved to be on the conservative side. For pillars at greater depths in excess of 150 m (this means the pillars must have higher w/h ratio), the equations of Obert - Duvall, and Holland-Gaddy including Salamon-Munro are too conservative and in fact were never envisioned for this purpose. Only the Mark-Bieniawski equation is still realistic up to a width to height ratio of 10 to 12. Madden (1991) emphasized this point and reported a modified 'Salamon-Munro Equation' for squat pillars of the following form:

$$C_p = k_M \frac{R_0^b}{V^a} \left\{ \frac{b}{\varepsilon} \left[\left(\frac{R_w/h}{R_0} \right)^\varepsilon - 1 \right] + 1 \right\} \quad (28)$$

Where k_M is the strength of coal sample (normally taken as 7.2 MPa), R_0 is the critical width to height ratio taken as 5.0, ε is the rate of strength increase taken as 2.5, a and b are constants which are determined statistically $a = 0.0667$ and $b = 0.5933$, R_w/h is the pillar width to height ratio. All the dimensions are taken in metres.

Pillar strength equation by Sheorey

Sheorey (1992) gave the equation for pillar strength as:

$$C_p = 0.27 \sigma_{c25} h_p^{-0.36} + \left(\frac{H}{250} + 1 \right) \left(\frac{W_s}{h} - 1 \right) MPa \quad (29)$$

Where, C_p is the strength of pillar (MPa), H is the seam depth, σ_{c25} is the strength of coal sample of size 25 mm cube, W_s is the solid pillar width (m), and h_p is the pillar height or working height (m). Equation 29 can be used for strength calculation of stooks as well. Since ribs are designed to fail eventually, Equation 29 was modified by Sheorey as follows:

$$C_p = 0.27 \sigma_{c25} \frac{\sqrt{W_s}}{h_p^{0.86}} MPa \quad (30)$$

Equation 30 was found to be a very good fit to the 14 failed cases and therefore is widely accepted for calculation of rib strength. The ribs are generally of low w/h ratio and one width is much greater than the other. Equation 30 can therefore be changed for long ribs to:

$$S = 0.4 \sigma_c \frac{\sqrt{W}}{h^{0.86}} MPa \quad (31)$$

It may be noted that Equation 31 should be used only for the strength calculation of long ribs whose shorter width (w) is such that $W/h \leq 3.0$.

Maleki equation for squat pillars

There exists a general belief that for squat pillars, the strength goes on increasing as the w/h ratio increases. The pillar becomes indestructible at a very high w/h ratio. However, Maleki (1992) reported failure of 7 US coal seams. His work based on numerical analysis, stress measurement and *in situ* closure grouped the 7 US coal seams into two and the best fit regression was given as:

$$C_p = 4700 \left[1 - e^{-0.339 \frac{W_p}{h_p}} \right] \text{psi}, \quad (32)$$

$$C_p = 3836 \left[1 - e^{-0.260 \frac{W_p}{h_p}} \right] \text{psi}, \quad (33)$$

Equation 32 was developed for strong seams analyzed on confinement control method. For seams where failure can be analyzed as structural control, the Equation 33 was derived accordingly.

Observation by Mark and Barton on pillar strength

Mark et al. (1997) summarized the work of a group of researchers who have determined that the value of *in situ* coal strength falls between 5.4 to 7.4 MPa. Mark et al. (1997) performed a statistical analysis that found no correlation between the stability of failed pillars and strength of coal specimen which indicated that pillar design was much more reliable when uniform coal strength was used. They identified many sources of unreliability in coal strengths viz. material variability within a particular seam, variation in sampling, specimen preparation, testing techniques and variation in size and shape effects between seams.

Observation by Gale on pillar strength

Gale (1999) viewed pillar as a system in which failure occurred in the strata rather than coal only; he came out with a wide range of pillar strength characteristics. The variations in these pillar strength characteristics were due to different strata - coal combinations not different coal strengths (Figure 3).

He concluded that the degree of confinement provided to the coal seam is a major factor in determining the pillar strength. If the roof and/or floor are themselves yielding and deforming (weak strata), under such circumstances the confinement the roof/floor which it can give to the coal rib side will drop.

Numerical method for pillar strength determination

Murali et al. (2001) used the strain softening option in FLAC3D to evaluate the pillar strength of 14- failed cases and 15- unfailed cases of Indian coal seams. The equivalent Mohr coulomb fit for Sheorey's failure criteria was used in the stain softening model. This modeling had a satisfactory agreement with the Sheorey's (1992) equation.

Sheorey (2006) reported numerical modeling studies for deep seated squat pillars of two mines, viz. Chinakuri No. 1 Mine and Jitpur Colliery using the strain softening model in FLAC3D. The results of numerical modeling were in good agreement with the Maleki (1992) squat pillar equation. The equations of Logie and Matheson. (1982), Madden (1991) and Sheorey (1992) predicted very high values in comparison with the modeled results.

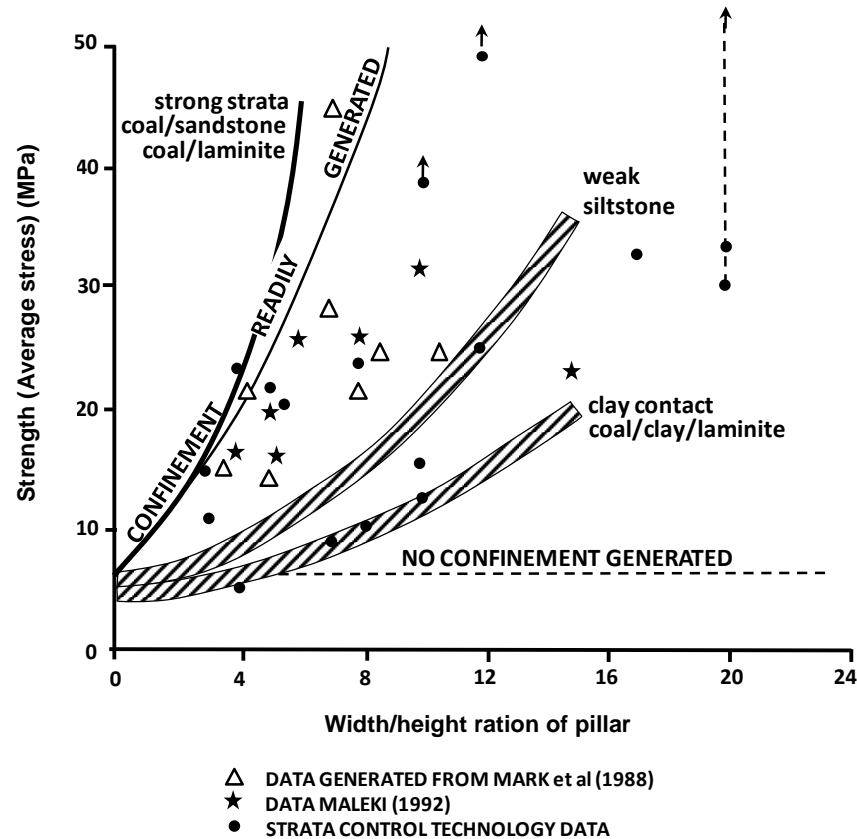


Figure 3. Strength and w/h for different geologic conditions (After Gale, 1999).

However, the post failure characteristics of the modeled pillar agreed well with the results for squat coal specimens.

Comparison of the pillar strength equations

Any pillar strength equation can be best judged by its suitability to fit the actual cases of pillar (stable or unstable). Sheorey (2006) elaborated the performance of some equations for failed and stable cases from Indian coalfields. The guiding philosophy for assessment of any pillar equation is, firstly the line of factor of safety = 1.0 must be the best fit for all collapse cases. Secondly, all stable cases must have a factor of safety higher than 1.0. Scrutiny of the pillar equations based on this principle, suggests that for Indian conditions, the Sheorey (1992) equation is the best predictor.

A graph of pillar strength prediction for different equations is shown in Figure 4. In order to compare these equations on a common platform, the height of pillar is kept constant to 3.0 m and the width is varied to observe the influence of width to height ratio on strength of the pillar. The strength of the coal is common wherever the equations demand it. The strength of laboratory size

specimen of 25 mm size is taken as 26 MPa and *in situ* strength of 30 cm specimen is taken as 7.6 MPa, a realistic value as reported by Sheorey (2006) for analysis of Begonia seam. The graph is interpreted in two parts, first the slender part (width to height ratio up to 6.0) and second, the squat part (Sheorey, Mark-Bieniawski, Madden Modified Bieniawski and Wilson, 1983; Case IIa equations). The baseline for best predictor is the Sheorey (1992) equation.

In case of slender pillars, it is observed that the Generalized Salamon-Munro equation (1967) is in close agreement with the Sheorey (1992) equation. The Grenwald equation (1941), Gaddy equation (1946) and Wilson equation Case IIa (1983) underestimates the pillar strength. Rest of the other equations viz. Cook et al. (1971), Obert and Duvall (1967), Mark-Bieniawski, Zern (1928) and Bieniawski (1975) overestimates the pillar strength.

In case of squat pillars, considering again the baseline as Sheorey (1992) equation, it is observed that the Zern (1928) equation initially over predicts the strength up to a w/h ratio of 14.0 and then under predicts the strength of the pillars beyond a w/h ratio of 14.0. A similar observation is made with respect to the Maleki (1992) equation for strong coal with a cutoff at a w/h ratio of 18.0

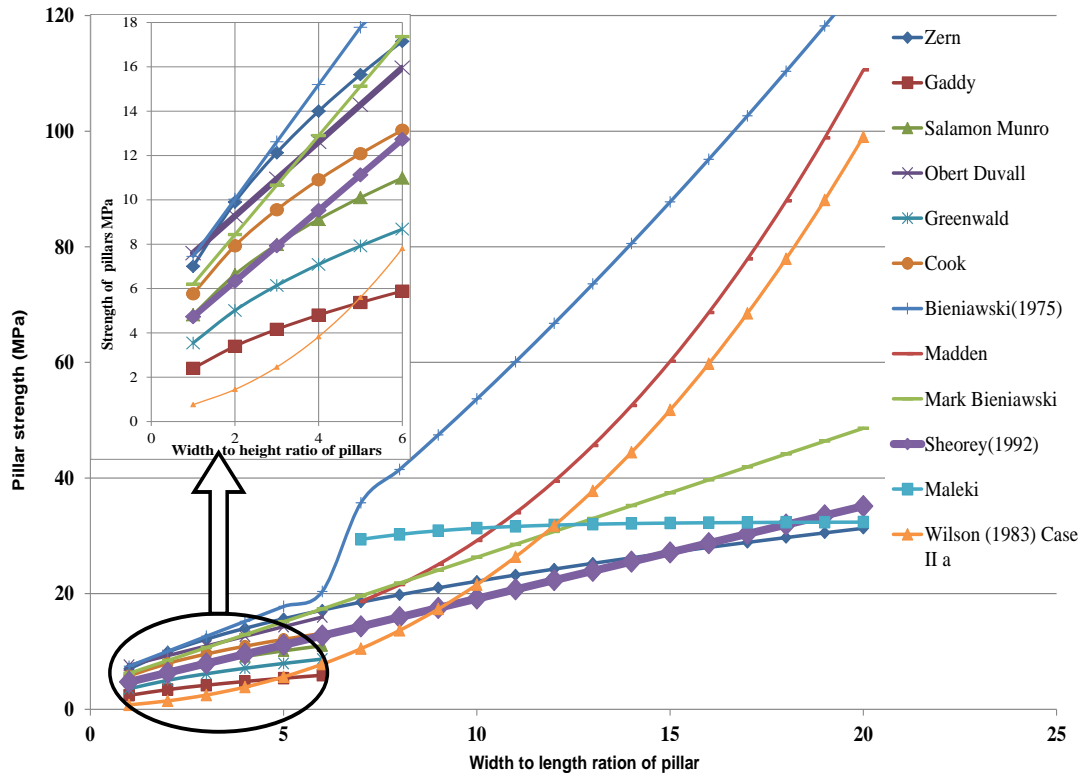


Figure 4. Comparison of different pillar strength equations.

and the Wilson (1983) equation Case IIa at a cut-off ratio of 9.0. Rest of the other equations of Mark-Bieniawski, Madden (1991) and Bieniawski and Van (1975) modified by Logie and Matheson (1982) over predicts the strength of squat pillars to a considerable value.

Conclusion

Different approaches for pillar design have been discussed in this paper. The suitability of the pillar design approaches, however, remain quite difficult as mentioned by Mark and Barton (1997) “despite the fact that textbooks have considered laboratory testing as an integral part of pillar design for nearly 30 years, it has remained controversial. One reason is that coal remains notoriously difficult to test.” The empirical methods are the best design approach towards the pillar design in particular conditions, provided they meet the performance criteria with respect to failed and stable cases of pillars. Any pillar design by numerical or other methods must be compared with the empirical relations of other workers as well as the locally developed empirical relations.

The Maleki (1992) observation of failed squat pillars throws light on the requirement of further research in the field of squat pillars. Numerical analysis of pillars based on elasto - plastic models is quite debatable especially with respect to the proper use of the input data and the

mesh size; this throws light on another grey area for pillar research through numerical methods.

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