American Journal of Mining and Metallurgy, 2014, Vol. 2, No. 1, 17-22
Available online at http://pubs.sciepub.com/ajmm/2/1/3

DOI:10.12691/ajmm-2-1-3

A Comparative Study of Various Empirical Methods to Estimate the Factor of Safety of Coal Pillars

A. K. Verma*

Department of Mining Engineering, Indian School of Mines – Dhanbad-04, Jharkhand, India
*Corresponding author: neurogeneticamit@gmail.com

Received April 21, 2014; Revised June 03, 2014; Accepted June 04, 2014

Abstract Design of coal pillars in a coal mine remains a challenge inspite of several theories proposed by several researchers over a period of time. India is heavily dependent on coal availability for supply of electricity to it's billion of citizens. This has burdened the coal industry to increase the coal production which ultimately has lead to extraction of coal pillars also. Coal pillars are used to support the overlying roof rock to prevent it from falling. The dilemma with coal pillar stability is that 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 stability of coal pillars has fascinated several researchers and hence many empirical equations have been proposed over the decades. In this paper, parameters like height of pillar, depth of pillar, compressive strength of coal, depth of the coal seam have been taken as input to estimate factor of safety of coal pillar from two mines i.e., Begonia and Bellampalli. It is found that Greenwald (1941), Salamon and Munro (1967), Sheorey (1992) and Maleki (1992) method has estimated failed cases correctly while Sheorey (1992) & Maleki (1992) have not predicted stable case of pillar correctly which is an interesting finding as empirical relations proposed by Sheorey (1992) is assumed to have good prediction in Indian condition.

Keywords: *Pillar strength, factor of safety, Begonia coal mines and Bellampalli coal mines, percentage deviation*

Cite This Article: A. K. Verma, "A Comparative Study of Various Empirical Methods to Estimate the Factor of Safety of Coal Pillars." *American Journal of Mining and Metallurgy*, vol. 2, no. 1 (2014): 17-22. doi: 10.12691/ajmm-2-1-3.

1. Introduction

The empirical coal pillar factor of safety approach is considered to represent the most reliable methodology available for analyzing the long-term stability of regular arrays of pillars that are wide with respect to cover depth. Alternative numerical approaches are hampered by our inability to accurately define rock mass properties and develop constitutive laws that fully define rock mass behavior. Board and Pillar mining method is one of the underground mining methods that commonly used for the extraction of coal seam in India. It involves driving two sets of parallel inseam headings, one set being orthogonal to another, thereby forming square or rectangular pillars. If the strength of a pillar in a room-and-pillar mine is exceeded, it will fail, and the load that it carried will be transferred to neighboring pillars. The additional load on these pillars may lead to their failure. Pillar strength can be defined as the maximum resistance of a pillar to axial compression. In flat lying deposits, pillar compression is caused by the weight of the overlying rock mass (Bieniawski, Z., 1968, 1984 & 1992). Empirical evidence suggests that pillar strength is related to both its volume and its shape. Numerous equations have been developed that can be used to estimate the strength of pillars in coal and hard rock mines, and have been reviewed and summarized in the literature. These equations are generally empirically developed and are only applicable for conditions similar to those under which they were developed (Jaiswal, 2009). More recently, numerical model analyses combined with laboratory testing and field monitoring have contributed to the understanding of failure mechanisms and pillar strength.

2. Parameter Influencing Stability of Pillars

Pillar strength can be defined as the maximum resistance of a pillar to axial compression. Pillars are the key load bearing elements of an underground coal mine. The stress on the pillars is a function of both the width (w) and the height (h) of the pillars. Several equations for calculating the pillar strength have been proposed by different researchers on the basis of laboratory test of rock.

Strength of coal pillars and their behavior can vary dramatically depending on their shape (Martin, 2000). Three broad categories of pillar behavior and failure mode have been identified, each defined by an approximate range of width-to-height ratios (Mark, 1999):

Slender pillars: - Slender pillars are those with w/h ratios less than about 3 or 4. When these pillars are loaded to their maximum capacity, they fail completely, shedding nearly their entire load. When large numbers of slender pillars are used over a large area, the failure of a single pillar can set off a chain reaction, resulting in a sudden, massive collapse accompanied by a powerful air blast.

Intermediate pillars: - Intermediate pillars are those whose w/h ratios fall between 4 and 8. These pillars do not shed their entire load when they fail, but neither can they accept any more loads. Instead, they deform until overburden transfers some weight away from it. The result is typically a non-violent pillar "squeeze," which may take place over hours, days, or even weeks. The large roof-to-floor closures that can accompany squeezes can cause hazardous ground conditions and entrap equipment.

Squat pillars: - Squat pillars are those with w/h ratios that exceed 10. These pillars can carry very large loads, and may even be strain-hardening (meaning that they may never actually shed load, but just may become more deformable once they "fail."). None the less, the pillar *design* may fail because excessive stress is applied to the roof, rib, or floor, or because the coal bumps. Moreover, the strength of squat pillars can vary considerably depending upon the presence of soft partings, weak roof or floor interfaces, and other geologic factors.

2.1. Empirical Pillar Strength Formulas

The design of coal pillar was started in 1773 by Coulomb as traced by Mark, 2006. However, Bunting (1991) designed first pillar for coal mines based on scientific approach. He carried out extensive laboratory test on different sizes of cube (2 to 6 inches size) & prism (2.25 to 12.25 inches height) of anthracite. He demonstrated that strength of coal prism has relation to their height and width.

Empirical pillar strength formulas were developed as part of major coal brook disaster whose main objective was to establish in situ strength of coal pillars. Salamon & Munro (1967) analyzed 125 case histories of Coal pillar collapse and proposed that the coal pillar strength could be determined using power formula

$$\sigma_p = K_{SM} h_p^{\alpha} w_p^{\beta} \quad \text{(i)}$$

Where σ_p (MPa) is the pillar strength, K_{SM} (MPa/m^2) is strength of a unit volume of coal and w & h are the pillar width & height in meters respectively. Hudson et al. (1972) after extensive laboratory study confirm that strength of a rock mass is too large part controlled by geometry by the geometry of the specimen i.e. w/h ratio. Equation (i) (Mohan, 2001) has been developed for Room & Pillar mining of horizontal coal seams. Following Bunting (1991), a number of pillar design equations were developed around the world as shown Table 1 a,b,c.

Das (1986) who observed that when w/h ratio increases beyond 4-6, the post failure characteristic starts ascending indicating a gain in strength (Figure 1). He also observed that at w/h ratio of 13.5, if pillars of such flatness are left in underground mines for support purpose, they can retain high strength even after failure.

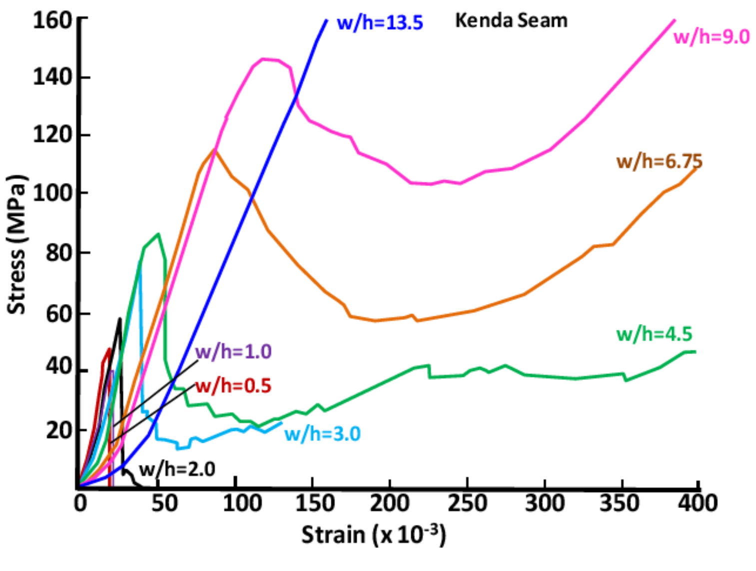

Figure 1. Influence of w/h ratio on the post-failure stress-strain behavior of coal (Das, 1986)

Table 1a. Proposed empirical relations for coal pillar strength determination

	Zern Edward Nathan (1928)	Greenwald (1941)	Salamon and Munro (1967)	Obert and Duvall (1967)
Empirical Relation	$C_p = C_1\sqrt{\left(\frac{w_p}{h_p}\right)}$	$C_p = 0.67k\frac{\sqrt{w_p}}{h_p^{0.83}}$	$Cp = k_{SM} h_p^{\alpha} w_p^{\beta}$	$C_p = C_{10}\left[0.778 + 0.222\left(\frac{w_p}{h_p}\right)\right]$
Remarks	Cp is pillar strength, C_1 is the coal strength, w_p is the pillar width and h_p is the pillar width.	Cp is the pillar strength, k is the strength of coal sample, w_p is the pillar width and h_p is the pillar height	Cp is the pillar strength, k_{SM}=7.176 kPa, h_p is pillar height, w_p is pillar width, α=-0.66, β=0.46	Cp is the compressive strength , C_{10} is the compressive strength of specimens having ratio of $\frac{d}{h}=1$, d is the diameter of the specimen, h is the height of the specimen
Limitations		Strength is calculated by unit cube of coal sample	K has to be evaluated by testing of specimen size 30 cm.	$\frac{d}{h}=1$

Table 1b. Proposed empirical relations for coal pillar strength determination

	Bieniawski (1975)	Logie and Matheson (1982)	Maleki (1992)
Empirical Relation	$C_p = k_B\left[0.64 + 0.34\left(\frac{w_p}{h_p}\right)\right]$	$C_p = k_B\left[0.64 + 0.34\left(\frac{w_p}{h_p}\right)\right]^{1.4}$	$C_p = 3836\left[1 - e^{-0.260\frac{w_p}{h_p}}\right]$
Remarks	Cp is the pillar strength, k_B is the compressive strength of a 30 cm cube pillar specimen(MPa), w_p is the width of the pillar, h_p height of the pillar	Cp is the compressive strength, k_B is the compressive strength, w_p is the width of the pillar, h_p is the height of the pillar	Cp pillar strength, w_p pillar width, h_p pillar height
Limitations	Specimen should be 30 cm cube pillar		

Table 1c. Proposed empirical relations for coal pillar strength determination

	Mark-Bieniawski (1997)	Sheorey (1992)
Empirical Relation	$C_p = S_1\left[0.64 + \left(0.54\frac{w_p}{h_p} - 0.18\left(\frac{w_p^2}{h_p L_p}\right)\right)\right]$	$C_p = 0.27\sigma_{c25}h_p^{-0.36} + \left(\frac{H}{250}+1\right)\left(\frac{w_p}{h_p}-1\right)$
Remarks	Cp is pillar strength, S_1 is in situ coal strength, w_p pillar width, h_p pillar height, L_p pillar length	Cp is pillar strength, H coal seam depth, σ_c strength of coal, w_p pillar width, h_p pillar height
Limitations		

2.2. Case Study

For comparison of suitability of various empirical relations, coal pillars at two mine namely Begonia in Raniganj coal field as failed pillar case and Bellampalli in Andhra Pradesh as stable pillar case have been chosen.

Any method for estimating pillar strength should satisfy the following two statistical conditions:

(a) All failed pillar cases should have a safety factor of 1.0. In statistical terms, this merely means that the line of safety factor=1.0 should be the best fit for a plot of pillar strength vs. pillar load.

(b) All stable cases must have a safety factor>1.0.

Parameters used for calculation of factor of safety for coal pillars at both Begonia & Bellampalli mine are shown in Table 2. Figure 2 shows the location of both Begonia & Bellampalli mines. Begonia mine is located in Asansol area of West Bengal while Bellampalli mine is located in Andhra Pradesh. Coal at Begonia mine has its origin from Raniganj sub group of upper Permian age while coal at Bellampalli has its origin from Barakar sub group of lower Permian age (Figure 3).

Table 2. Different parameter value for Begonia (failed) and Bellampalli (stable) case

S.No.	Mines	Depth of coal seam	Pillar height (h in m)	Pillar width (w in m)	w/h ratio	Compressive strength of coal sample
1.	Begonia	36	3	3.9	1.3	26
2.	Bellampalli	36	3	5.4	1.8	48

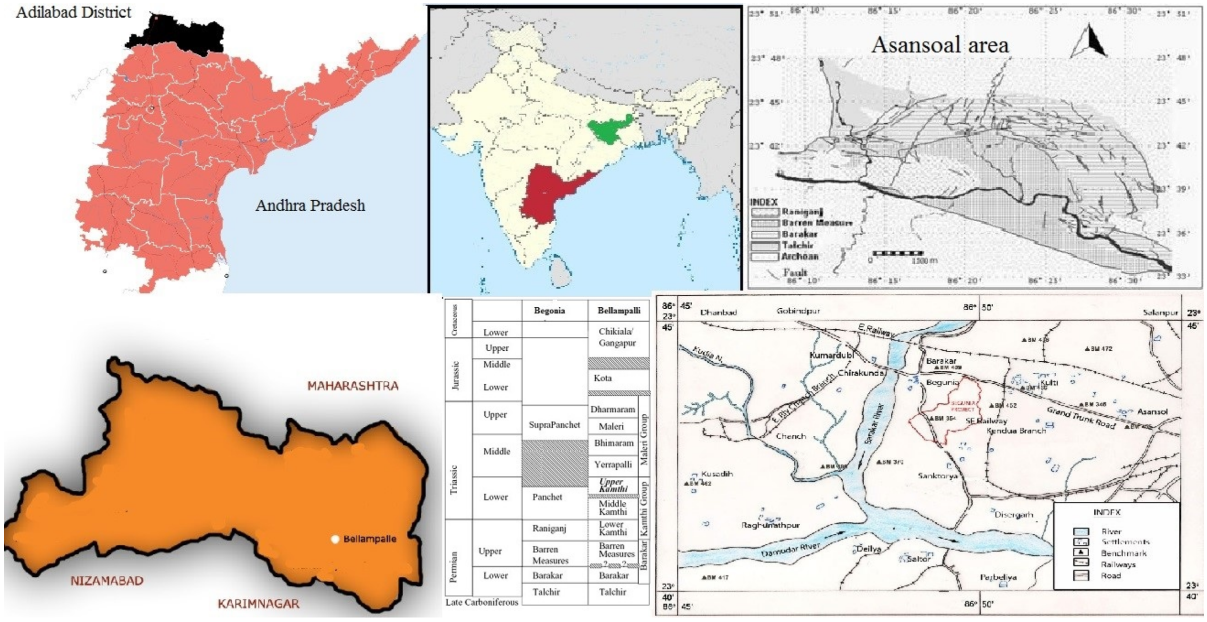

Figure 2. Location map and stratigraphy (Mukhopadhyay, 2010) of Begonia and Bellampalli coal mines

Parameters used for calculation of factor of safety for coal pillars at both Begonia & bellampalli mines is shown in Table 2. Figure 2 shows the location both Begonia and Bellampalli mines. Begonia mines is located in Asansol area of West Bengal while Bellampalli mines is located in Andhra Pradesh. Coal at Begonia mines has its origin from Raniganj formation of upper Permian age while coal at Bellampalli has its origin from Barakar formation of lower Permian age (Figure 2).

Table 3. FoS estimated by different empirical relations and their % deviation from critical factor of safety 1.0

Researchers	Failed Case		Stable Case	
	FOS	% deviation from FOS of 1.0	FOS	%deviation from FOS of 1.0
Zern Edward Nathan (1928)	1.48	48	2.9	190
Greenwald (1941)	0.69	-31	1.3	30
Salamon and Munro (1967)	1.17	17	2.3	130
Obert and Duvall (1967)	1.38	38	2.6	160
Bieniawski (1975)	1.40	40	2.7	170
Logie and Matheson (1982)	1.45	45	3.0	200
Mark-Bieniawski (1997)	1.44	44	2.8	180
Sheorey (1992)	0.40	-60	0.8	-20
Maleki (1992)	0.37	-63	0.45	-55

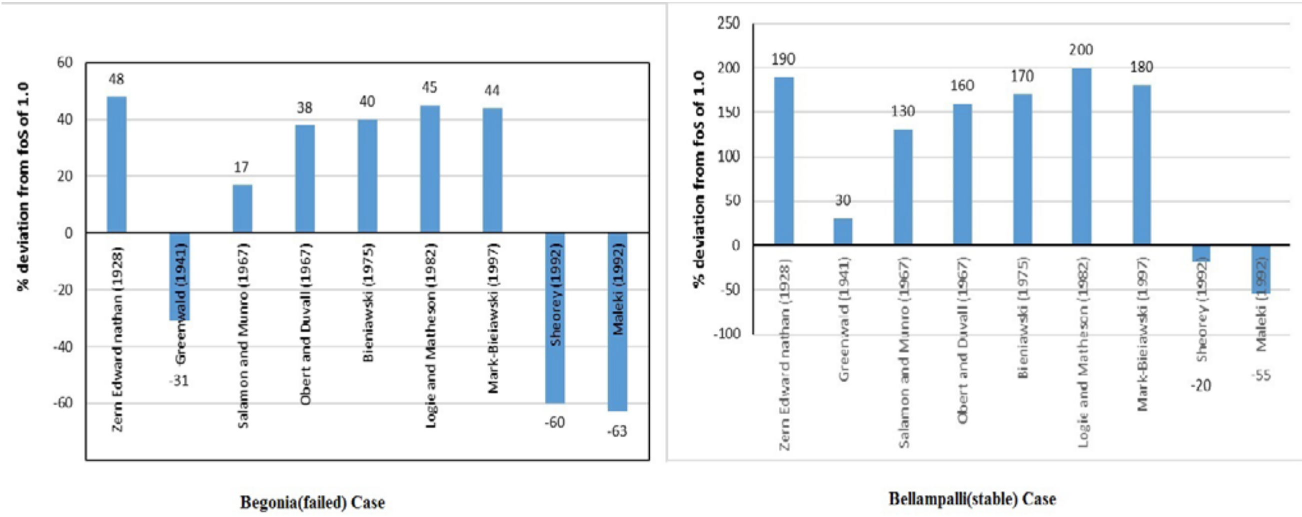

Figure 3. percentage deviation from FOS of 1.0 for Begonia (failed case) and Bellampalli (stable case) by different empirical relation

Figure 3 and Table 3 shows the percentage error deviation of factor of safety from 1.0 which is assumed to be the boundary line between the stable and failed cases. The empirical equation which gives us the negative percentage of deviation from the boundary line of FOS of 1.0 is correct for failed case. It can be observed that Greenwald (1941), Salamon and Munro (1967), Sheorey (1992) and Maleki (1992) method has estimated failed cases correctly.

Similarly the empirical equation which gives the positive percentage error deviation from the assumed boundary line of critical FOS of 1.0 will be correct estimation of FOS for stable coal pillar case. All empirical equation has predicted correct trend of FOS for stable coal pillar case except Sheorey (1992 &1986) & Maleki (1992).

In the stable case only two methods have given the wrong estimation in negative percentage deviation from the boundary line 1.0. For the second case, all the empirical relation given by different researchers has given the positive percentage deviation only 'Sheorey' and 'Maleki' has given the negative parentage deviation.

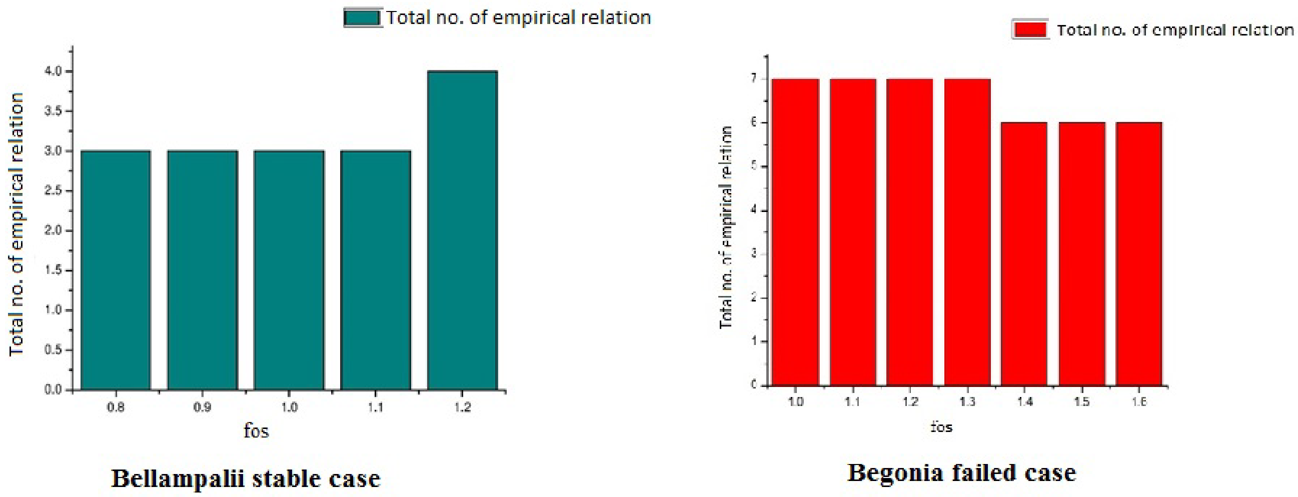

Figure 4. Number of empirical relation predicting stable cases and failed cases at different critical FOS

Figure 4 show the number of empirical relation predicting the coal pillar stable & failed cases at different value of FOS. Figure 6 show that if we assumed critical FOS of 1.2 , the four empirical can predicted the failed Begonia coal pillar case while FOS range of 0.8 to 1.1, number of empirical equation predicting failed Begonia coal pillar critical FOS is constant and have value of 3. Similarly for critical FOS range of 1.0 to 1.3, the number empirical relation predicting Bellampalli coal pillar stable case was seven while there are six empirical relations between FOS ranges of 1.4 to 1.6.

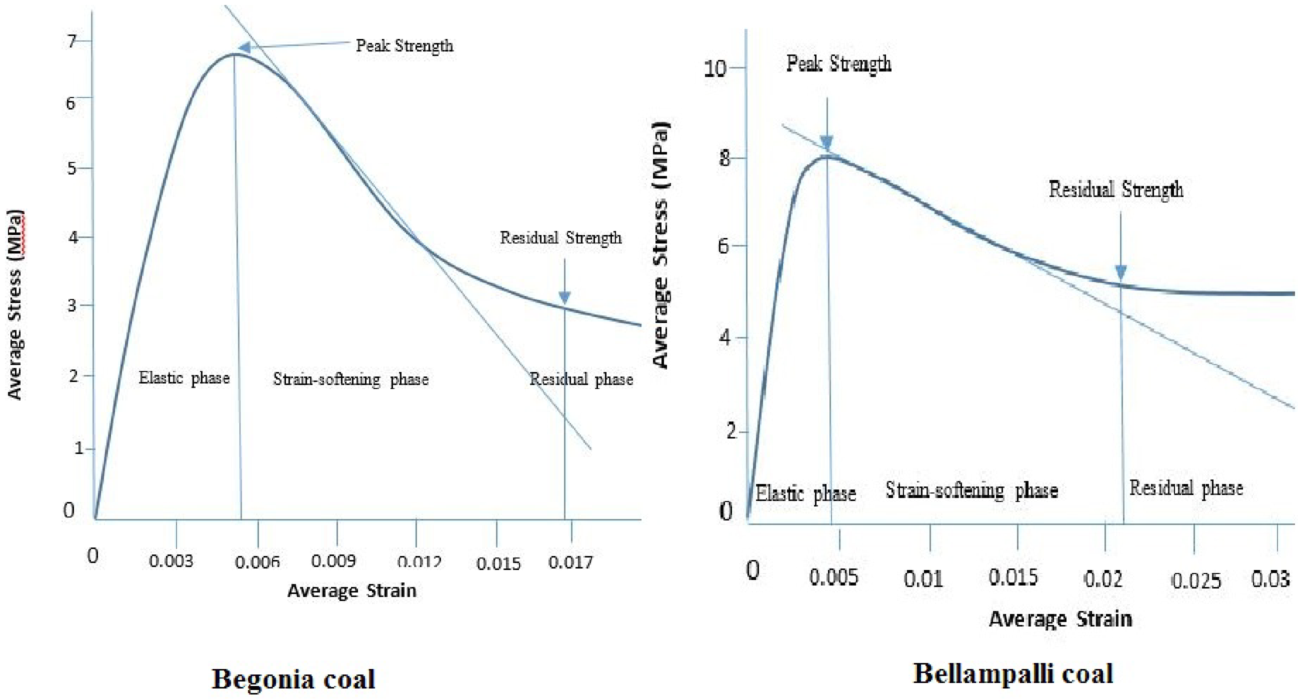

Figure 5. Average strain and average stress curve for Begonia coal and Bellampalli coal

Figure 5 shows the stress-strain curve and different zone of stable of stress for both Begonia and bellampalli coal.

There are three main regimes: pre- failure, the strain-softening zone, and the residual zone. Peak strength is characterized by a peak failure criterion. It is dependent on the state of stress conditions. Strain-softening behavior is characterized by both the failure criterion and the plastic potential. The last phases of perfectly plastic are characterized by the residual failure criterion along with a plastic potential. Bellampalli coal has higher strength as compared to Begonia coal.

Strength of Indian pillar coal increases after w/h ratio of 5 which is suggested by observation of Das (1986).

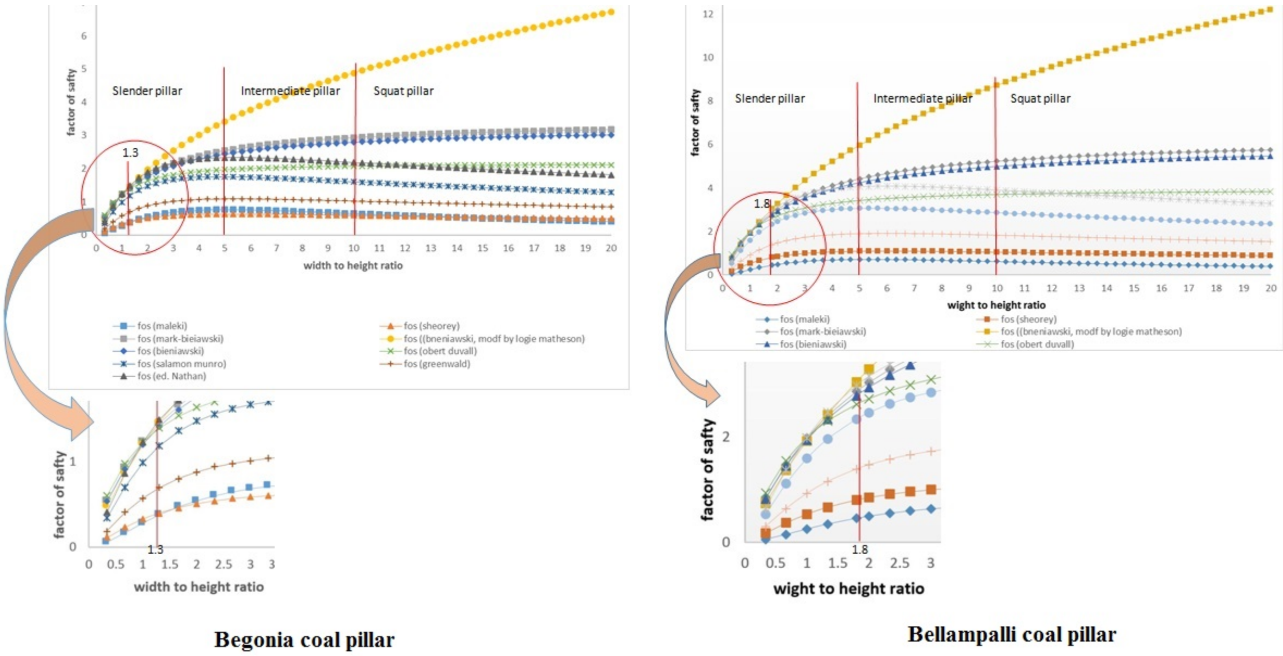

Figure 6. Variation of Begonia coal pillar and Bellampalli coal pillar FOS with w/h ratio

Figure 6 shows increase in FOS with increase in width to height ratio of Bellampalli coal pillar. In the case of slender pillar and also the case of Bellampalli coal pillar (w/h = 1.8) highest FOS of pillar is predicted by Logie and Matheson (1982), Bieniawski (1975) and Mark-Bieniawski (1997) while least strength is predicted by Maleki(1992) and Sheorey(1992). Similar trend is shown in case of Bellampalli coal pillar (Figure 6).

3. Conclusion

In this paper, empirical and analytical pillar design relations proposed by several researchers have been discussed. It is found from the above study that in order to use these relations successfully, it is necessary to obtain the different input parameters realistically which is difficult due to uncertainties in determination of coal properties. Since pillar cases are quite old, the input parameters are generally based on experience. Even though, this empirical technique has a good potential for realistic prediction.

In the present study, the effect of width to height ratio of coal pillar of two mines i.e., Begonia and Bellampalli on its stability has been considered. It has been found that pillar strength is almost linearly dependent on w/h ratio less than 5 and non-linearly dependent on uniaxial compressive strength of the coal specimen. It is concluded that Greenwald (1941), Salamon and Munro (1967), Sheorey (1992) and Maleki (1992) method has estimated failed cases correctly while Sheorey (1992) & Maleki (1992) have not predicted stable case of pillar correctly which is an interesting finding as empirical relations proposed by Sheorey (1992) is assumed to have good prediction in Indian condition. In the case of Begonia coal pillar (w/h = 1.38), highest strength and FOS is predicted by Logie and Matheson (1982), Bieniawski (1975) and Mark- Bieniawski (1997) while the least strength and FOS is predicted by Maleki (1992) and Sheorey (1992). Similarly, in the case of Bellampalli coal pillar (w/h = 1.8) highest strength and FOS of pillar is predicted by Logie and Matheson (1982), Bieniawski (1975) and Mark-Bieniawski (1997) while least strength and FOS is predicted by Maleki (1992) and Sheorey (1992).

References

[1] Bieniawski, Z. T, Balkema (1984): A. A. Rock Mechanics Design in Mining and Tunneling; 272 pp.

[2] Bieniawski, Z. T. (1992): A method revisited: coal pillar strength formula based on field investigations, proceedings, workshop on coal pillar mechanics and design, Bu mines; p 158-165.

[3] Bieniawski ZT. (1968): In situ strength and deformation characteristics of coal; Volume 2, 325-40.

[4] Bunting, D. (1991): Chamber Pillars in Deep Anthracite Mines. Trans. AIME; vol. 42, pp. 236-245.

[5] Christopher Mark. (1981-2006): Chief, Rock Mechanics Section NIOSH-Pittsburgh Research Laboratory Pittsburgh, PA, USA, The evolution of intelligent coal pillar design.

[6] Das, M.N. and Sheorey, P. R. (1986): *Triaxial Strength behavior* of some Indian coals. Journal of Mines, Metals & Fuels; 34 (3). pp. 118-122.

[7] Hudson, J.A., Brown, E.T. and Fairhurst, C. (1972): Shape of the complete stress-strain curve for rock. In Proc. 131h Symposium on Rock Mechanics, Urbana, Illinois, Edited by E.J. Cording; pp: 773-795.

[8] Jaiswal, Ashok, Shrivastva, B.K. (2009): Numerical simulation of coal pillar strength, International Journal of Rock Mechanics & Mining Sciences; Volume 46, 779-788.

[9] Jawed, M., Sinha, R. K. and Sengupta, S. (2013): Chronological development in coal pillar design for board and pillar workings: A critical appraisal, Journal of Geology and Mining Research; Vol. 5 (1): pp. 1-11.

[10] Mohan, G. Murali, Sheorey, P.R., Kushwaha. A. (2001): Numerical estimation of pillar strength in coal mines, International Journal of Rock Mechanics & Mining Sciences; Volume 38, 1185-1192.

[11] Mark, C. (1999): Empirical Methods for Coal Pillar Design. Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design. U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health (NIOSH); IC 9448, pp. 145-154.

[12] Martin,C.D., Maybee, W.G. (2000): The strength of hard-rock pillars, International Journal of Rock Mechanics & Mining Sciences; Volume 37; 1239-1246.

[13] Maleki H. (1992): In situ pillar strength and failure mechanisms for US coal seams. In: Proceedings of the workshop on coal pillar mechanics and design, Pittsburgh, US States Bureau of Mines; p. 73-8.

[14] Mukhopadhyay, G., Mukhopadhyay, S. K., Roychowdhury, M and Parui, P. K. (2010): Stratigraphic Correlation between Different Gondwana Basins of India, journal geological society of india; Vol. 76: pp. 251-266.

[15] Salamon MDG, Munro. A.H. (1967): A study of the strength of coal pillars. J. South Afr. Inst. Min. Metallurgy; 68:55-67.

[16] Sheorey, P. R., Das, M. N., Bordia, S. K., Singh B. (1986): Pillar strength approaches based on a new failure criterion for coal seams, International Journal of Mining and Geological Engineering; Volume 4: pp 273-290.

[17] Sheorey PR. (1992): Design of coal pillar arrays, chain pillars. In: Hudson JA, et al., editors. Comprehensive rock engineering, vol. 2. Oxford: Pergamon; p. 631-70.