Longwall barrier design: a perspective

Nair, Roshan
National Institute of Rock Mechanics, India
Sastry, V.R.
National Institute of Technology Karnataka, India

Abstract

This paper discusses existing design methodologies used in designing barriers for a underground longwall panel and their application have been reviewed. A comparison of outcomes from some of design with current practice adopted in India for arriving at barrier widths is also presented in the paper. There is a need to adopt barrier design methodology based on extensive study of complex interaction process during longwall extraction.

1. Introduction:

The per capita commercial primary energy consumption in India is expected to be 450kgoe/year by 2010 which is well below that of developed countries and can be attributed to rising population, expanding economy and improved quality of life (1). Several policy initiatives in energy sector may fall short of demand, considering the limited reserve potentiality of petroleum and natural gas, eco-conservation restriction on hydro-electric power projects and geo-political perception of nuclear power. In India, the gross reserves of coal are presently estimated at around 255.17Bt with proven reserves of 97.92Bt, sufficient to last the next century at an annual rate of production of over 500Mt (2). The annualized coal demand could vary from 4.7 per cent to 7.27 per cent till 2032 to achieve a sustained GDP growth of 8 per cent per annum as compared to the annualized growth in consumption of 5.6 per cent over the last 25 years for an average GDP growth of about 5.51 per cent/annum (3). The total production of coal has increased by 6.29 per cent annually from 336.87Mt in 2002-03 to 456.98Mt in 2007-08 (4). However, with planned high percentage of GDP growth, there is a significant need to have accelerated coal production. Environmental implications of open cast coal mining demands higher production from deep seated deposits and use of highly mechanized methods of mining. Though longwall mining has proved its potential in other countries, their application in Indian mining scenario has been average. The success of a longwall method is associated with performance of selected equipment and state of geological and geomechanical factors encountered during mining. Barriers are key component in a longwall layout as it not only protects the gate roads from roof falls but also to bear load being transferred from the roof (strata control), to isolate spread of fire from one panel to another and to reduce ingress of water into the working panel. Design of barriers range from methods developed from back-analyses of failed and successful case histories, extrapolation from strength tests on small-scale coal samples to full-size coal pillars, empirical and analytical formulae based on limiting stress distribution across the barrier and recommendations from numerical modeling studies. Thus, there is need to adopt a single design equation applicable to the entire range of coal pillars and conditions.

2. Design of barrier:

The longwall barrier design method should be relevant to both the geological conditions at the site and the function of coal strength being considered (5). The types of barriers used in longwall panel vary in different countries. Chain pillars with two or three entry system are used in countries like United States and Australia, whereas in India and South Africa, longwall panel consists of barriers with single entry or two entries. Some of the mines in United States and Australia use yield pillar-chain pillar system while barrier-less longwall mining is employed in China. In Europe, advancing longwall method of extraction is practiced which does not require any significant design of barriers. Accordingly, the methods used for design of barriers (pillars) in longwall vary considerably in these countries. This paper deals with the exhaustive review of some main design methods used in longwall mining. The various design methods are discussed below:

2.1 Analysis of Longwall pillar stability (ALPS):

ALPS, proposed by United States Bureau of Mines (USBM) in 1990, is the most commonly used approach for conventional longwall chain pillar design in the United States (6). The ALPS divides load transferred to the pillar into two parts, consisting of development load and abutment loads. The development load is calculated using tributary area load (TAL) and abutment load is based on a wedge concept of overburden on chain pillars. Abutment angle used to estimate the abutment loads was defined by King and Whattaker (7). Accordingly, the side abutment load can be estimated as:

$$L_s = \frac{\gamma H^2 \tan\beta}{2} \qquad \text{for critical and super critical panels}$$

$$L_{ss} = \gamma\left(\frac{HW_m}{2} - \frac{W_m^2}{8\tan\beta}\right) \qquad \text{for sub critical panels}$$

Where,

H = Overburden depth (ft)
W_m = Panel width or face length (ft)
γ = Unit weight of overburden (pcf)
β = Abutment angle (assumed as 21^0)

ALPS estimates the front abutment load of 0.5 times L_s for main gate and 0.7 times L_s for tail gate. Chain pillar strength is estimated by Bieniawski equation, as follows:

$$B_p = \frac{144\ \sigma_p\ L_p}{L_p + W_E}$$

Where,

σ_p = Compressive strength of coal (psi)
L_p = Length of the pillar (ft)
W_E = Width of the pillar (ft)

The strength of total system of chain pillar is obtained by summation of the strengths of all individual pillars. A stability factor of 1.0 - 1.3 is suggested for design of stable chain pillar system by ALPS method. This method is limited by its empirical approach in estimating pillar strength and pillar loading. The abutment angle used in ALPS remains constant of 21^0, and can lead to over estimation of abutment load as the depth of seam increases (8 and 9). ALPS utilized gate road width to determine stress distribution and pillar load, but did not evaluate its effect on stability of gate roads. ALPS have not evaluated the effect of roof and floor quality on the validity of design method.

2.2 Hsiung and Peng's Chain pillar design method:

Hsiung and Peng's method directly incorporates properties of the roof and floor, such as young's modulus of coal, immediate roof, main roof and floor, into the pillar design. The method compared ultimate compressive strength of pillar to pillar load for evaluation of chain pillar stability. This method was developed from numerical model by using three-dimensional finite element model and multi-variable regression technique and pillar width is given by (10):

$$\log w = -4.676\times10^{-3}\frac{E_i}{E_c} - 4.04\times10^{-3}\frac{E_m}{E_c} - 3.33\times10^{-2}\log\frac{E_f}{E_c} - 7.29\times10^{-2}\log\sigma_c$$
$$+ 0.5144\log H + 0.0494\log\frac{L}{2} + 0.1941\log W_m$$

Where,

w = Chain pillar width (ft)
E_i = Young's modulus of immediate roof (psi)
E_c = Young's modulus of coal (psi)
E_m = Young's modulus of main roof (psi)
E_f = Young's modulus of floor (psi)
σ_c = Uniaxial compressive strength of laboratory coal specimen (psi)
H = Overburden depth (ft)
W_m = Panel width or face length (ft)
L = Panel width (ft)

The method was based on the three entry system. Thus, result gives the width of one row of chain pillar. The advantages of this method are the elimination of yield zones at the pillar edge and the simplicity in determining the pillar width. Accuracy of the formula depends directly on the accuracy of model. The method estimates front and side abutment load by finite element model simulation, which includes caving, partial compression of gob, roof or floor failure, pillar edge failure, and roof to floor convergence. The design method was based on modified Coulomb criteria to define yield of the coal mass. The method was developed from detailed simulation and is more accurate than the conventional 2-D simulation. The design method does not incorporate any real caving mechanism. However, the method bypasses this limitation by evaluating model element's strength to developed stress at each mining step, and replacing the element in the goaf with broken roof element when stress level is greater than the element's strength. Eight parameters, considered in the method, form a comprehensive list of potential design parameters. The method has fixed the internal friction angle of coal as 37^o. This parameter dominates the effect of confinement on pillar compressive strength. Effect of high horizontal stress on the pillar stability was considered in the basic numerical model. The method did not evaluate the effect of entry width on both pillar and gate road stability.

2.3 Choi and McCain Chain pillar design method:

This method combined the results from field studies, numerical modeling and practical experience (11). Pillar load and strength estimate are combined into a single equation:

$$P = 0.6H - 1.2\left[\frac{H^2}{4} - \frac{5}{3}\left(\frac{w_A L_p}{L_p + w_e} \times \frac{\sigma_p}{24.9SF} - w_A H - \frac{w_e H}{2}\right)\right]^{0.5}$$

Where,

σ_p = Pillar strength (KPa)
L_p = Pillar length (m)
H = Overburden depth (m)
w_A = Pillar width (m)
w_e = Entry width (m)
SF = Safety factor (recommended 1.3).

Pillar strength estimation was made on the basis of empirical Holland-Gaddy formula. The formula does not directly estimate required pillar width, which is a disadvantage of the formula. The method did not consider horizontal stress in the mine. Choi and McCain method considers the affect of entry width in stress estimation, but the method does not evaluate the effect roof and floor quality on the stability of entry and pillar. The method does not reveal the stage of extraction in the panel along with the condition of goaf. The method was developed in the region where seam depth was upto 300m.

2.4 Carr and Wilson's method:

Wilson's confined core model is one of the first models to analytically estimate pillar strength (12). Wilson's confined core model predicts the distribution of stress inside a coal pillar. The basis of model is that the compressive strength of brittle materials, such as coal, can be enhanced by confinement. The model assumes that coal follows Mohr-Coulomb's failure criterion. Carr and Wilson (13) assumed that pillar consists of two zones, an outer yield zone and an elastic inner core based on load transfer during extraction. They postulated that the yield zone can take no more loads on failure, but it provides constraint to the core, which usually take most of the load-bearing capacity of the pillar. Initially, maximum stresses in the pillar are found at the boundary between the two zones. As additional longwall loadings are applied, stress in the pillar core increases till it reaches the peak stress at the yield zone boundary. Pillar and entries adjacent to it remain stable until this point, which was termed as the Limit of Roadway Stability (LRS). Further loading of the pillar causes yield zone to expand and results in increased horizontal stresses that can damage the nearby gate road. Finally, the entire core yields as ultimate limit (UL) is reached. The total side abutment load was calculated by:

$$L_{ss} = 0.5W_m\gamma\left(H - \frac{W_m}{1.2}\right) \qquad \text{when } W_m < 0.6H$$

$$L_{ss} = 0.5\gamma H^2 \qquad \text{when } W_m > 0.6H$$

Where,

W_m = Panel width (ft)
H = Overburden depth (ft)

Three possible cases were considered for pillar stability in the method:

1. Initial loading stage- During this stage, edge of pillar loses their confinement and starts to yield. This yield zone can not take more load. It provides a constraint for the elastic pillar core, due to the frictional resistance between the yielded pillar edges and the roof-and-floor of the excavation. Peak stress in the pillar is found at the boundary between yield zone and the core. The entry may be damaged without load transfer if the applied stress exceeds the LRS, but remains less than the UL.
2. Limit roadway stability (LRS) stage - As additional longwall loadings are applied, average stress in the pillar core increases until it equals the peak stress at the yield zone boundary. During this stage, both the pillar and entries adjacent to it are stable.
3. Ultimate limit (UL) of resistance stage - Further loading of the pillar causes yield zone to expand. Finally, maximum bearing capacity of the pillar is reached when the entire core has yielded. Wilson assumed that the pillar maintains its ultimate loading capacity, UL, even at failure. The additional load, called the transferred remnant load (TRL), is carried over to the adjacent pillar row when the applied load is greater than the UL of chain pillar.

Two possible boundary conditions were assumed at the coal pillar/rock interfaces:

1. Rigid roof and floor (RRF) condition in which the yielding only takes place in coal pillar.
2. Yield roof and floor (YRF) condition in which yielding takes place all around the entry.

Wilson provided equations to determine the width of yield zone and the distribution of vertical and horizontal stresses in that zone during the LRS loading stage for the proposed boundary conditions. Carr et al. (14) proposed design method using a pillar resistance to load ratio or stability factor and suggested that a stability factor of 1.4 should be used for abutment pillars subjected to tailgate loading, while 1.0 is adequate for single-use pillars. The method is used extensively in Jim Walter Resources (JWR), US, for sizing chain pillars in longwall. Disadvantage of the model is that any discrepancy between the data used for the design and the in-situ data reduces the accuracy of the method. The design method utilizes a simplified subsidence model to estimate pillar loading. The subsidence model provides an acceptable level of accuracy for engineering design, provided that there are no large geological variations such as the presence of a thick strong bed in relatively weak strata. The method also does not evaluate the effect of entries. The method assumes a uniform stress field, thus, no consideration for horizontal stress is available. Quality of roof and floor are considered only to provide confinement of pillar.

2.5 Sheorey's Method of designing chain pillar:

This method was developed to design chain pillars for bord and pillar mines in Indian condition (15). However, the method has been discussed as it is the only technique available for design of pillars in Indian geomining conditions. The design was based on tributary area method for load calculation at development stage and Wilson's concept for estimating side abutment load. The method considers horizontal stress in a mine and the influence of entry width over stress distribution in the pillar. The properties of roof strata were considered based on its rock quality designation (RQD), and cavability characteristics. Design was proposed for condition of goaf on one or both the sides of the chain pillar. The load was calculated based on mining conditions in the panel as given in Table 1. The strength of chain pillar was calculated based on CMRI pillar strength equation, given as:

$$S = 0.27\sigma_c h^{-0.36} + \left(\frac{H}{250}+1\right)\left(\frac{W_1}{h}+1\right)$$

Where,

S = Pillar strength (MPa)
σ_c = Compressive strength of 1" coal cube (MPa)
H = Overburden depth (m)
w = Width of the pillar (m)
h = Extraction height (m)
The notations in the table are as follows:
P = Load on chain pillar (MPa)
γ = Unit weight of rock (0.025/m depth of overburden)
L = Panel widths (m)
F = Goaf treatment factor, 0.3 for caving and 0.2 for stowing
W = Length of the pillar (m)

Table 1
Estimation of load transferred on the chain pillar (15)

Sl.	Mining condition	Formula for load (MPa)
1	Single row of chain pillars with goaf on both the sides	
a	Cavable strata or stowing when $L_1<2fH$, $L_2<2fH$	$p = \frac{\gamma(W_1+B)}{WW_1} + \left[H\left(W_1+\frac{L_1+L_2}{2}\right) - \frac{1}{8f}\left(L_1^2+L_2^2\right)\right]$
b	Cavable strata or stowing when $L_1<2fH$, $L_2>2fH$	$p = \frac{\gamma(W_1+B)}{WW_1} + \left[H\left(W_1+fH+\frac{L_1}{2}\right) - \left(\frac{f}{2}H^2+\frac{1}{8f}L_1^2\right)\right]$

c	Cavable strata or stowing when $L_1 \geq 2fH$, $L_2 \geq 2fH$	$p = \frac{\gamma(W_1 + B)}{WW_1} + H(W_1 + fH)$
d	Difficult caving conditions	$p = \frac{\gamma(W_1 + B)}{WW_1} + H\left(W_1 + \frac{L_1 + L_2}{2}\right)$
2	Two row of chain pillars with goaf on both the sides	
a	Cavable strata or stowing when $L_1 < 2fH$, $L_2 < 2fH$	$p = \frac{\gamma(W_1 + B)}{2WW_1} + \left[H\left(2W_1 + B + \frac{L_1 + L_2}{2}\right) - \frac{1}{8f}\left(L_1^2 + L_2^2\right)\right]$
b	Cavable strata or stowing when $L_1 < 2fH$, $L_2 > 2fH$	$p = \frac{\gamma(W_1 + B)}{2WW_1} + \left[H\left(2W_1 + B + fH + \frac{L_1}{2}\right) - \left(\frac{f}{2}H^2 + \frac{1}{8f}L_1^2\right)\right]$
c	Cavable strata or stowing when $L_1 \geq 2fH$, $L_2 \geq 2fH$	$p = \frac{\gamma(W_1 + B)}{2WW_1} + H(2W_1 + B + fH)$
d	Difficult caving conditions	$p = \frac{\gamma(W_1 + B)}{2WW_1} + H\left(2W_1 + B + \frac{L_1 + L_2}{2}\right)$
3	Long chain pillars without interconnections: In all the above formulae, remove (W_1+B) and W_1	
4	Chain pillars with goaf on one the side	
a	Cavable strata or stowing	$p = \frac{(W_1 + B)}{WW_1} + \left[\gamma H\left(W_1 + \frac{B}{2}\right) - A\left(1 - e^{-\alpha\left(W_1 + \frac{H}{2}\right)}\right)\right]$ $\alpha = \frac{(n-1)\gamma H}{A}$ $A = \frac{f}{2}\gamma H^2$ if $L_1 \geq 2fH$ and n =0.5 (for caving) n =3.5 (for stowing) $A = \frac{\gamma L_1}{2}\left(H - \frac{L_1}{4f}\right)$ if $L_1 < 2fH$ and $n = 5.7\left(1 - e^{\frac{-3.4L}{H}}\right)$ $A = \frac{\gamma L_1}{4}\left(H - \frac{L_1}{4f}\right)$ if $L_1 < 2fH$ and $n = 3.8\left(1 - e^{\frac{-5.5L}{H}}\right)$
b	Difficult caving conditions	Formula difficult to derive and numerical modeling should be used

2.6 Subsidence engineering method for design of rib pillars:

Design of longwall pillars in this method is based on the assumption that the pillars are virtually indestructible and sustain overburden stresses. This method used Bieniawski's pillar strength formula for strength prediction of coal pillars based on large scale in-situ tests on square pillars. Strength of the pillar (S) can be extrapolated by using the following equation:

$S = 2\ 76 + 1379\ (w/h)$

Where,

S = Strength of the pillar (MPa)
w = Width of the barrier (m)
h = Height of the barrier (m)

King's approach (7) was used to estimate load transferred on the barrier. This approach was based on the assumption that barriers have to sustain the load transferred from the roof due to excavation, apart from the overburden pressure. The caved material in the goaf carries only the weight of strata which is enclosed by the inward angles of draw (average value taken as 31°). The increased barrier load is given by the following equation:

$P = (7.34 \times 10^5)\ (LD - 2(\cot \Phi/4))$

where,

P = Load on barrier (MPa)
L = Face length (m)
D = Depth below surface (m)
Φ = Limiting angle

This method mainly depends on the comparison between the strength and load over barrier. Applicability of this approach is restricted because of the assumptions that the increased pressure is uniformly distributed across the barrier. However, stress distribution in the barrier is not uniform (16).

2.7 Whittaker and Singh's method for design of rib pillars:

Whittaker and Singh (17) used Salmon's pillar strength formula to design longwall pillars. Pillar size is given by the following equation:

For w/h ratio < 2tan Φ (narrow extraction)

$$h\ (p + w) = (w^2\ (\cot \Phi/4)) + (7.32 \times 10^5\ p^{1.46}/\ \sigma\ Fm^{0.88})$$

For w/h > 2tan Φ

$$h^2 + ph = (7.32 \times 10^5\ p^{1.46}/\ \sigma\ Fm^{0.65})$$

Where,

h = Depth below surface (m)
σ = Average density of overburden (kg/m^3)
p = Width of rib pillar (m)
w = Width of longwall face (m)
Φ = Average angle of shear of strata hanging over goaf (°)
F = Factor of safety (1.3 -19)
m = Pillar height (m)

This method over-designs the width of rib pillars, however, can be justified for designing protective pillar for a set of longwall faces (16).

2.8 Coal mine regulation (CMR) 112-4:

Barrier design of longwall mines in India is based on the procedures given in Coal Mine Regulations (CMR) 122-(4). The recommended barrier widths are based on the width of gallery and depth of seam from the surface. The barrier widths recommended are given in Table 2 (18). The regulations were developed for bord and pillar method of extraction and later extended to longwall mining. According to the regulations, the size of pillar increases considerably with depth. Nearly one third of the coal is left unutilized in the form of barriers in panel at depth exceeding 360m. In longwall mining, complete panel is extracted whereas some pillars are intentionally left behind in bord and pillar method. Thus, the regulations gave significant importance to the size of galleries which may not hold true for design of barriers in longwall mining.

Table 2
Recommended barrier widths according to CMR 112-4 (18)

Depth of seam from surface	**Where the width of galleries does not exceed 3.0m**	**Where the width of galleries does not exceed 3.6m**	**Where the width of galleries does not exceed 4.2m**	**Where the width of galleries does not exceed 4.8m**
	The distance between centers of adjacent pillars shall not be less than (m)			
Not exceeding 60m	12.0	15.0	18.0	19.5
Exceeding 60m but not exceeding 90m	13.5	16.5	19.5	21.0
Exceeding 90m but not exceeding 150m	16.5	19.5	22.5	25.5
Exceeding 150m but not exceeding 240m	22.5	25.5	30.0	34.5
Exceeding 240m but not exceeding 360m	28.5	34.5	39.0	45.0
Exceeding 360m	39.0	42.0	45.0	48.0

3. **Conclusions:**

The CMR 112 (4) recommends larger barrier width till 300m depth in comparison with other popular design methods like Shoerey's formulae, Hsuing and Peng method and ALPS for the same design inputs i.e. compressive strength of coal as 6.2MPa (Figure 1). The variation was found to be an average of 38 per cent, 26 per cent and 81 per cent for Shoerey's formulae, Hsuing and Peng method and ALPS respectively. Beyond 350m of depth, Shoerey's method and ALPS suggest higher barrier widths in comparison to CMR112 (4). However, the recommendation of CMR112(4) remains constant for deeper depth which may not be sufficient in bearing the overburden load at deeper depths. As CMR 112(4) was developed basically for bord and pillar method, a separate design recommendation is required for longwall mining. There has been no significant research on the longwall method of mining to improve its applicability in Indian geomining conditions. Hence there is need to have detailed design methodology to arrive at barrier widths for underground longwall coal mines. The methodology should be based on scientific study involving numerical modeling incorporating geological and geomechanical feature of Indian coal fields and detailed instrumentation in longwall panels in order to back analyze the results leading to a judicious design of barriers in longwall mining.

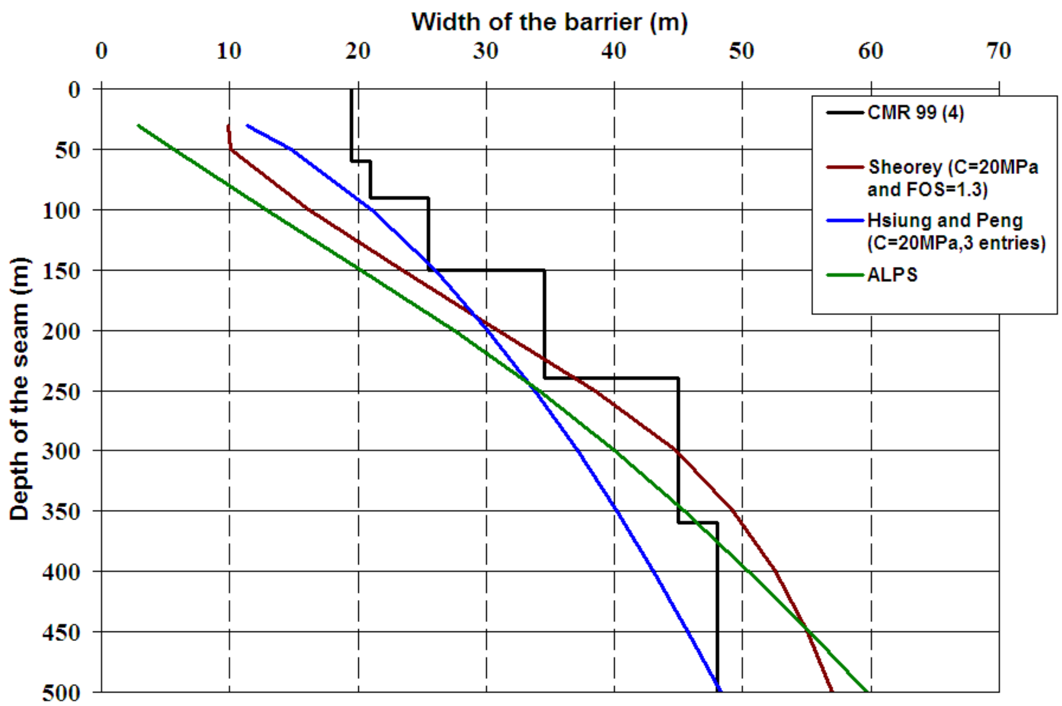

Figure 1 Comparison of pillar widths obtained from different longwall barrier methods

References:

1. Anon (2007). Annual coal report 2006, Energy Information Administration, tables 1; 26; 27; 28; and 34; DOE/EIA-0584 (2006), Washington, DC.
2. Anon (2007). Coal resource scenario of India, Coal wing, Geological Survey of India.
3. Anon (2006). Integrated energy policy, report of expert committee, Planning Commission, Government of India, New Delhi
4. Anon (2008). Coal production statistics, Ministry of Coal, India, www.coal.nic.in
5. Cassie, J.W., Altounyan, P.F.R, and Cartwright, P.B. (1999). Coal pillar design for longwall gate entries, International Workshop on Coal Pillar Mechanics and Design, Information Circular 9448, 23-32.
6. Mark, C. (1992). Analysis of Longwall Pillar Stability (ALPS): update, Proceedings of theWorkshop on Coal Pillar Mechanics and Design, United States of Department of the Interior, USBM, 238-249.

7. King, H. J., and Whittaker. B.N. (1971). A review of current knowledge on roadway behaviour, Proceedings of Symposium on Roadway Strata Control, IMME, 6, 73-87
8. Heasely, M. (2000). The forgotten denominator: pillar loading, Proceedings of 4th North American Rock Mechanics Symposium, Seattle, WA, 457-464.
9. Colwell, M., Frith, R., and Mark, C. (1999). Analysis of longwall tailgate serviceability (ALTS): a chain pillar design methodology for Australian conditions, Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design, NOISH IC 9448, 33-48
10. Hsiung, S. M., and Peng, S. S. (1985). Chain pillar design for U.S. longwall panel, Mining Science and Technology, 2(4), 279-305.
11. Choi, D. S., and McCain, D. L. (1979). Design of longwall system, Proceedings of Mini-Symposium on Underground Coal Mine Design and Planning, SME-AIME Annual Meeting, Atlanta, GA, 15-26.
12. Wilson, A. H. (1977). The effect of yield zone on the control of ground, Proceedings of 6th International Strata Control Conference, Banff Spring, Canada.
13. Carr, F., and Wilson, A. (1982). A new approach to the design of multi-entry developments for retreat longwall mining, Proceedings of the 2nd Conference on Ground Control in Mining, West Virginia University, Morgantown, WV, 1-21.
14. Carr, F., Gardner, B.H., and Martin, E. (1984). How to eliminate roof and floor failures with yield pillars, Coal Mining Process, Strata Geomechanics Inc., Richmond, CA, 21(12), 60-70
15. Sheorey, P.R. (1993). Design of coal pillar arrays, chain pillars, Comprehensive Rock Engineering, 2, Oxford, Pergamon, 631–670.
16. Singh, R.N., Pathan, A.G., and Ünver, B. (1987). Design of rib pillars in longwall mining based on theoretical and practical approaches, Proceedings of the 10th Mining Congress of Turkey, Ankara, Turkey, 23-28.
17. Whittaker, B.N., and Singh, R.N, (1979). Evaluation of the design requirements and performance of gate roadways, The Mining Engineer, 138, 535-553.
18. Anon (2006). The coal mine regulation, 2006, DGMS circulars, http://www.dgms.in/