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Optimal Underground Extraction of Coal at Shallow Cover Beneath Surface/Subsurface Objects: Indian Practices

By

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Summary

Considering ground instability problems of underground coal mines at shallow covers, this paper reviews and describes problems of optimal extraction of coal stuck below surface/subsurface constraints at Indian coal fields. Importance of thickness and quality of inter-burden between the working horizon and surface/subsurface constraints is discussed from a ground movement point of view during optimisation of coal recovery by underground mining beneath the constraints. A CIMFR, formerly CMRI idea, known as Wide Stall Method, was found suitable to overcome the limitations of non-effective-width based optimisation of recovery of coal, trapped in pillars below surface/subsurface objects, at shallow cover. The involved rock mechanics concept and three successful field trials of the Wide Stall Method under three different geo-mining conditions of the country are also briefly given in this paper.

Keywords: Underground, recovery, wide-stall, coal-mining, surface/subsurface constraints.

1. Introduction

In India, opencast mining is a better option for the exploitation of coal reserves at shallow cover mainly due to its high production and productivity. Better performance of this mining method is mainly due to adoption of large scale mechanisation for rock/coal excavation. Productivity of underground mines of the country is, relatively, poor due to lack of mechanisation but, at present, underground mining is being preferred over opencast mining because of the growing concern about the associated environmental impact. Complete stowing of the void with incombustible material is a solution to overcome the ground control problems of underground mining at shallow cover. But, stowing of underground voids is cost and labour intensive and, at a number of places, the non-availability of a sufficient quantity of stowing material affects the production and productivity adversely. An assessment of environmental impact of mining reveals that the underground mining is a part of clean coal technology (Singh, 1999). Relatively, little surface alteration is required for underground mine related activities. Also, the impact of deeper underground excavation on the overlying surface environment is negligible. But underground mining of coal below shallow cover causes considerable damage to surface and sub-surface objects due to a large amount of ground movement, surface subsidence and, some times, due to discontinuous subsidence.

In India, percentage of coal recovery during development of a coal seam by formation of pillars remains low because the gallery width cannot be more than 4.8 m (CMR, 1957). Further, final underground extraction of these pillars is difficult due to presence of overlying surface structures like buildings, rivers, forests, etc. There are a number of cases where the presence of overlying sub-surface features like heavily charged aquifers, underground voids of old workings, etc. forces the industry to adopt a partial extraction method during underground mining. Depth of cover is an important parameter for the selection of a suitable mining method for underground extraction of a coal seam. The effect of this parameter was well established by mining engineers even before the advent of modern rock engineering concepts. This is the reason for the age-old practice to increase the pillar size with depth of cover (Table 1), which is a familiar example of the practical importance of the parameter. The governing rock engineering norms of underground mining at shallow cover are different from those at deeper cover. It is worth mentioning here that, generally, the stability of excavations close to surface is mainly controlled by rock structure while the stability of deeper excavations is more influenced by the properties of intact rock and pre-existing stresses (Hudson and Harrison, 1997).

Wide Stall Mining with hydraulic sand stowing was reported earlier (Singh and Singh, 1999) but two successful field trials of this approach without stowing were completed recently. Considering the geo-mining conditions of Indian coal fields, this paper first reviews the role of depositional conditions for optimal underground mining of coal below surface/subsurface features. A simple analysis of stability of the underground structures associated with room and pillar working of a coal seam provides scope for Wide Stall Mining for a particular band-width of the geo-mining conditions. Three case studies (including two new field trials without stowing) are also briefly presented to show the potential of this method for optimal underground extraction of coal at shallow cover.

Table 1. Pillar size variation as per regulation 99 of Indian Coal Mines Regulations, 1957 (after CMR, 1957)

Depth cover, m	Pillar size (centre to centre) for different roadway widths (B), m			
	B = 3.0	B = 3.6	B = 4.2	B = 4.8
Below 60	12	15	18	19.5
60–90	13.5	16.5	19.5	21
90–150	16.5	19.5	22.5	25.5
150–240	22.5	25.5	30.5	34.5
240–360	28.5	34.5	39.5	45
Above 360	39.0	42	45	48

2. Geo-Mining Limitations

Room and pillar are the two basic initial structures for underground mining of coal. Under varying thickness of overlying strata, each of these two structures may face limiting situations where problems related with their instability become extreme. The first extreme situation arises due to the presence of inadequate thickness of hard strata over an excavation at shallow depth of cover. Under this condition the chance of collapse of the entire rock-mass column up to the surface is high which may cause severe surface damage. The chance of occurrence of the second extreme situation is high at deeper cover because the value of vertical stress over a pillar increases with increase in depth of cover (Fig. 1).

It has been observed that the room and pillar workings of Indian coal mines at deeper cover (>200 m) generally experience considerable side spalling[1] of pillars causing considerable reduction in their strength. Ultimately this process of spalling may lead to crushing of the pillar. If a pillar gets crushed at a higher depth of cover, redistribution of stresses may affect the stability of neighbouring pillars resulting in progressive crushing of a number of surrounding pillars, one after another. Occurrence of this phenomenon for a seam standing on pillars at deeper cover and with relatively high percentage of extraction during pillar formation may increase the dimension of the failure area big enough to disturb the surface structures.

Even in the absence of a high value of mining-induced stresses, presence of shale/soil band in the coal seam and the condition of the underground environment (Salamon et al., 1998) may induce pillar spalling. Pillar spalling due to these two

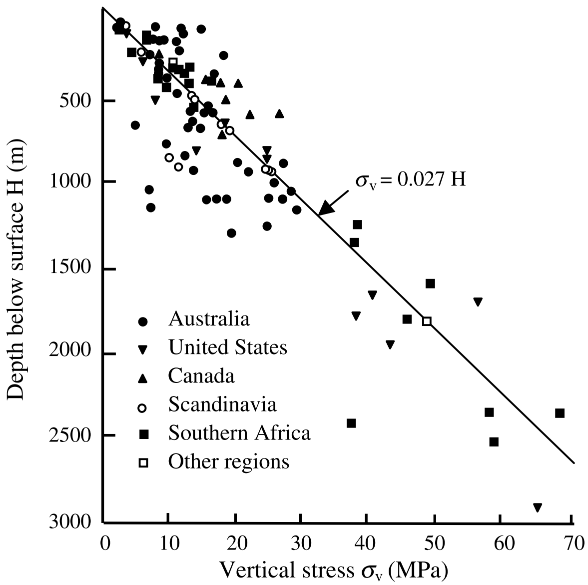

Fig. 1. Variation of *in situ* vertical stress with depth cover (after Hoek and Brown, 1980)

[1] This reduces the effective size of the pillar resulting in a threat for the safety of the pillar

reasons may take place at any site and is not dependent upon the depth of cover and percentage of extraction. However, two parameters (discontinuous subsidence and competency of rock mass) are of considerable importance for underground mining of coal at shallow cover. These will be discussed in the following.

2.1 Discontinuous Subsidence

Coal extraction from an underground mine starts with the formation of an opening in the form of gallery/gate-road. An increase in width of the opening disturbs the natural state of strata equilibrium and roof strata movement takes place due to the removal of natural support by the excavation. The movement of strata penetrates inside the overlying rock mass with an increase in the dimension of the excavation. With further increase in dimension of the excavation, the immediate roof strata caves in and the movement keeps advancing towards the surface. Ultimately, the movement/deformation of overlying strata, with increase in dimension of excavation, travels up to the surface and subsidence is noticed. However, at shallow cover, collapse of the entire rock-mass column over the excavation up to the surface (formation of pot holes/ discontinuous subsidence) takes place due to the presence of inadequate overlying hard cover. In comparison to continuous subsidence phenomenon (Saxena et al., 1989), the discontinuous subsidence causes severe surface damage as it occurs in shear steps.

Singh (2000) has explained the pot hole formation phenomenon and identified six parameters responsible for it, which are: shallow cover, weak overburden, geological discontinuities, rainfall, removal of hydrostatic support and earthquakes. However, the pot hole formation phenomenon is also related with the *in situ* stress condition. In fact, dependence of horizontal stress on elastic modulus of rock (Sheorey et al., 2001) keeps the shallow cover region generally free from high stress condition. The rock

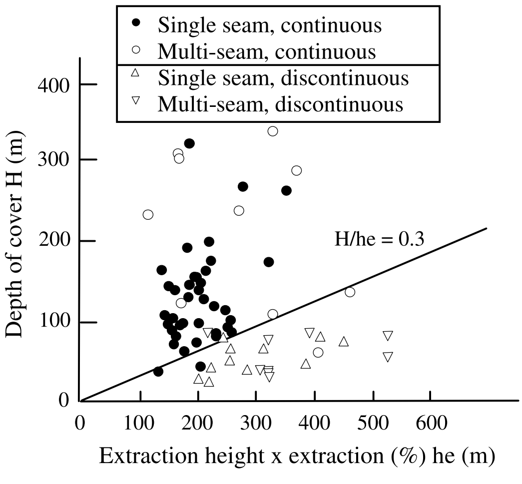

Fig. 2. Line of demarcation between continuous and discontinuous subsidence (after Sheorey et al., 2000)

strata, close to surface, are often in a fractured state. Poor side confinement due to low horizontal stress condition in top-soil/loose-cover increases the chance of collapse of the entire thickness of the overlying rock-mass column up to the surface causing pot holing/discontinuous subsidence. On the basis of different field studies in India, a line of demarcation between continuous and discontinuous subsidence cases (Fig. 2) was established at CMRI (Sheorey et al., 2000). This line of demarcation is found valid for, both, single and multiple seam mining cases and the relationship is expressed as:

$$H/he = 0.3 \tag{1}$$

where H is depth of cover, h is working height and e is percentage of extraction.

2.2 Competency of Rock Mass

Another important point for optimal coal extraction at shallow covers is competency of the overlying rock mass. Increase in width of an opening keeps adding load over the roof strata. The opening experiences roof instability when the load exceeds the strength of the roof strata. One simple way to assess the height of strata movement/deformation in a roof rock mass above the opening is based (Wilson, 1983) on the angle of internal friction (ϕ) as visualised in Fig. 3. For a competent formation, the value of ϕ remains high, resulting in less height of broken roof strata above the opening. Therefore, an opening of considerable width below competent overlying strata may not cause surface subsidence. Maximum width of the opening, which does not cause any surface subsidence, is articulated as non-effective width (NEW) and is expressed as a width-to-depth ratio. NEW may not be of much relevance for softer coal measures and, probably, this is the reason why the Subsidence Engineer's

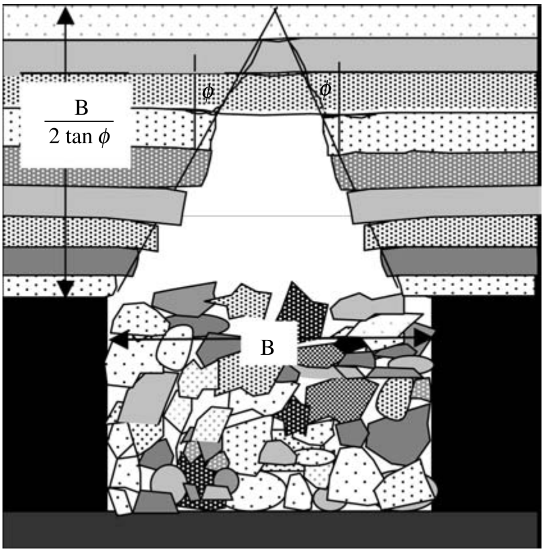

Fig. 3. Estimation of cavity height formed in roof rock mass of a gallery

Handbook, UK (NCB, 1975) does not mention it. The observed value of NEW varies between 0.2 and 0.8 for Indian coal fields and depends upon overlying strata characteristics (Sheorey and Singh, 1996).

Due to favourable techno-economic reasons of the country, coal seams below important surface/subsurface structures have extensively been developed on room and pillars where only up to 30–35% recovery is made. Optimisation of recovery from these coal seams, standing on pillars, needs detailed study of the geo-mining conditions of the site. One way to optimise the recovery is to control the dimension of excavation as per the non-effective width of the site. The value of safe span from the non-effective-width concept increases with the cover of the coal seam, so different dimension of excavation may be adopted for different cover over the seam if the depth of the seam varies considerably. This process to control the dimension of underground excavation is very important when damage of the overlying surface/subsurface structures is not allowed. However, there are surface/subsurface structures, which can tolerate a certain extent of damage due to underground mining, but the critical limit of the damage is not well defined. In fact, the process of interaction becomes extremely complex. Here, the establishment of a safe limit of damage is, probably, site and structure specific and falls beyond the scope of this paper.

It is very difficult to obtain a high percentage of coal recovery during subsidence free underground mining at shallow covers. The developing rock-mechanics/strata-control norms have proved to be useful in optimisation of coal recovery with relatively safer underground structures (Sheorey and Singh, 1996; Singh and Singh, 1999). In this regard, application of NEW to control the dimensions of underground excavations for no disturbance in surface/subsurface properties is an important development and is being practiced by the Indian coal mining industry.

3. Non-Effective Width of Mining

One way to optimise the recovery from a coal seam standing on pillars is to control the dimension of excavation as per the non-effective width (NEW) of the site. The idea of NEW experienced considerable attraction in Indian coal fields because this provides scope for the optimisation of recovery from a coal seam stuck below a surface constraint. If surface/subsurface deformation is not allowed and the width of the underground excavation is matched with the safe span from NEW, then the stability of the natural supports *i.e.* pillars is of vital importance.

Application of NEW for subsidence free extraction can be done in two ways: (a) simply by leaving a row of stable chain pillars between two goafs[2] of non-effective widths and (b) goaf-pillar method. In the latter method, long-term stable pillars are left inside the goaf in such a way that the maximum width of excavation formed all around these pillars remains non-effective. In fact, for the long-term stability of underground structures of a developed coal seam, the value of the safety factor of the standing pillars should not be less than 1.5, rather a safety factor value equal to 2 or more than

[2] Area where final extraction has been made is called goaf. A filled/packed goaf is called stowed goaf while unfilled goaf is called caved goaf

2 is preferable. Pillar strength (S) is estimated (Sheorey, 1992) by the following relationship:

$$S = 0.27 \times \sigma_c \times h^{-0.36} + (H/250 + 1)(W_e/h - 1)\ \text{MPa} \tag{2}$$

where

σ_c = uniaxial compressive strength of coal in MPa,
h = working height in m,
H = depth of cover in m,
W_e = effective pillar width = $4A/P_c$
A = area of pillar = $L_1 \times L_2$ and
P_c = perimeter of the pillar (corner to corner) = $2 \times (L_1 + L_2)$
L_1 = length of the pillar (corner to corner) and
L_2 = width of the pillar (corner to corner).

Load on the chain pillars left in between NEW panel is obtained by following Wilson's (1983) formula:

$L_P \geqslant 2fH$

$$P = 0.025H/(W^2)[(W + f \cdot H)(W + B)\ \text{MPa} \tag{3}$$

$L_P \leqslant 2fH$

$$P = 0.025/W^2[(W + L_P) \cdot H - {L_P}^2/4f](W + B)\ \text{MPa} \tag{4}$$

where

L_P = panel width, m
H = depth, m
f = 0.3 for caving
= 0.2 for stowing
W = pillar width (corner to corner)
B = width of gallery, m.

Average width of extraction (NEW) at the time of appearance of the first symptom of surface subsidence can easily be estimated for a symmetrical shape of excavation. But the estimation of NEW for an irregular shape of excavation is, generally, difficult. The equivalent NEW for an irregular shape of excavation can be estimated through numerical modeling and considering equal height of disturbance (Loui and Sheorey, 2002). NEW is an important parameter for the subsidence prediction norms for Indian coal fields. The empirical equation (Sheorey et al., 2000) to predict maximum subsidence (S) for single seam mining cases is given as:

$$S = 0.33[1 + 1.1\tan h(1.4(x - 1.8))] \tag{5}$$

where $x = (L/H)/NEW$ and L is width of the panel.
Observed variation of maximum subsidence with (L/H)/NEW is shown in Fig. 4.

Optimisation of recovery becomes a problem at shallow covers, when surface damage is not desirable and the value of the NEW becomes smaller than the dimension of a pillar. Under this condition, even, alternate row of pillars cannot be

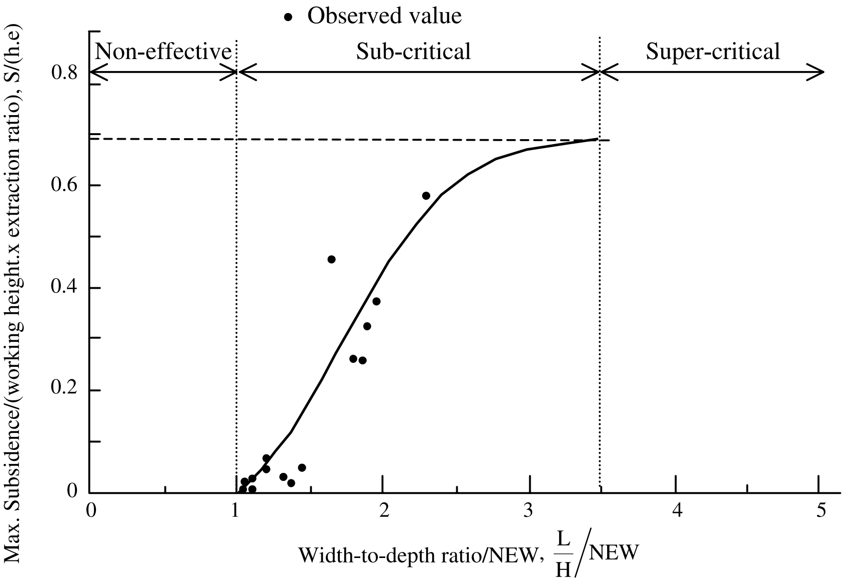

Fig. 4. Maximum subsidence for single seam cases (after Sheorey et al., 2000)

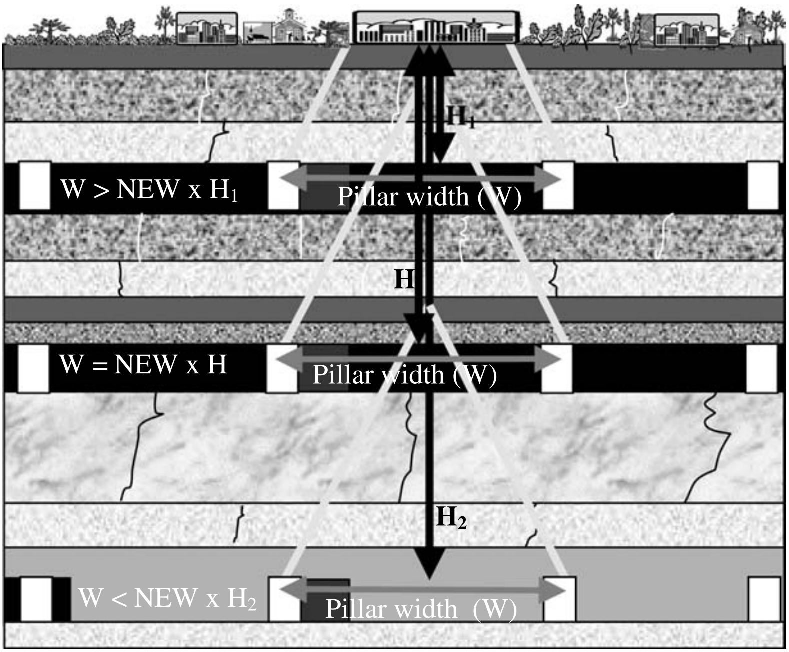

Fig. 5. Suitability of NEW for complete pillar extraction under variable depth cover

extracted without damaging the surface features (Fig. 5). Here a partial extraction method called wide stall (Singh et al., 1992; Mandal and Dubey, 1999) becomes a safer option.

4. Wide Stall Method (WSM)

As discussed above, thickness and quality of inter-burden between the working horizon and surface/subsurface structures are the two most important parameters for optimisation of coal recovery by underground mining. Both parameters affect percentage of recovery from the coal seam. The application of a concept, termed NEW, to control the dimensions of underground excavations for optimal recovery of coal, trapped in pillars below surface/subsurface structures, is an established practice in the Indian coal industry.

A higher value of safe span from the non-effective width at a deeper seam provides enough width of the excavation to accommodate row/rows of the developed pillars for final extraction. At shallow cover, when the value of the safe span becomes smaller than the width of a single pillar then even alternate row of pillars cannot be extracted without endangering stability of the surface/sub-surface features. This is the situation where the Wide Stall Method (WSM) can be practiced to arrest the chance of occurrence of discontinuous subsidence. With a simple basic concept, WSM was first adopted (Singh and Singh, 1999) to optimise recovery from a developed thick coal seam with stowing at East-Bhugatdih mine.

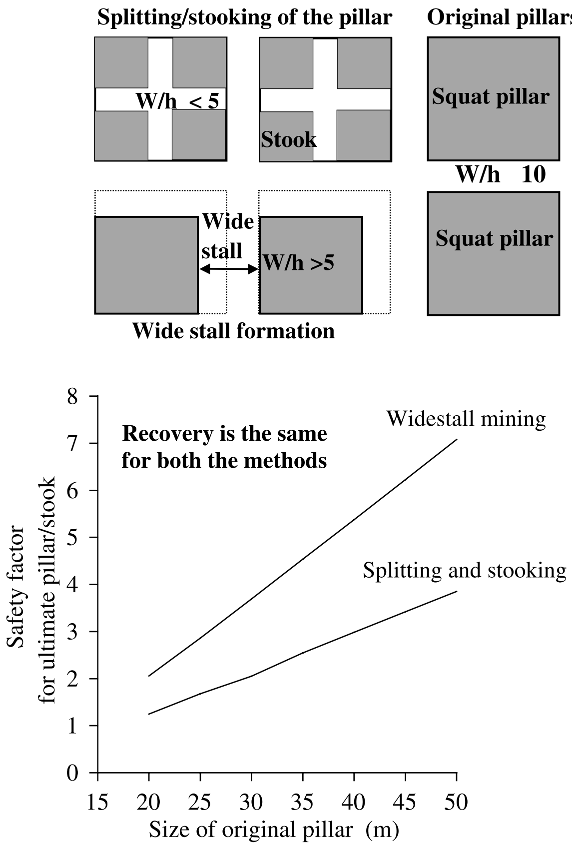

Fig. 6. Comparison of wide stall mining with conventional splitting and stooking of a pillar

For a room and pillar working if the roof is competent then the roof span and hence the room width can be increased to increase the recovery of coal. The conventional method of splitting and stooking of a pillar, to optimise the recovery of coal under built-up surface structures has limited scope under massive immediate roof strata at shallow depth of cover. Pillars formed during development of a coal seam, as per Indian coal mines regulations, generally, have safety factor more than 2 and width to height ratio (w/h) more than 5. Taking advantage of the rapid increase of pillar strength with the increase in its size, the conventional splitting and stooking method to optimise recovery under built up surface structure is replaced by widening of the existing galleries in a particular configuration and the method is called WSM (Fig. 6). As per the Indian coal mines regulations, the maximum allowed width of galleries is 4.8 m only, while during wide stalling this width is extended up to 9.0 m.

Matching of the gallery size with the strength of immediate roof and strength improvement of the pillar *i.e.* natural support by increasing w/h ratio (in comparison to splitting and stooking) are the two basic constituents of the WSM philosophy. Strength of ultimate pillars and stability of overlying exposed roof span play important roles for long-term stability of a wide stall under shallow depth of cover. Conventional splitting and stooking for optimisation of recovery during partial extraction under surface/sub-surface features reduces the strength of the pillar support and brings the cores of the resulting stooks under the increasing effect of mining induced stress (Singh et al., 1992).

Stress redistribution on pillars during splitting and stooking and Wide Stalling is visualised by numerical modeling. For this purpose, a boundary element method (Crouch and Starfield, 1983) using BESOL[3] was used for simulation of the geo-mining conditions of the site. Vertical *in situ* stress (S_v) at the site was taken as γH (γ is average unit weight of the overlying rock mass) while the horizontal *in situ* stress (S_h) for the numerical model was estimated by the relation:

$$S_h = 3.75 + 0.015H \tag{6}$$

Figure 7 shows the contours of mining induced stresses (vertical) for conventional splitting and stooking and wide stalling. Simulation of both processes with numerical modeling visualised the above discussed fact that the core of ultimate pillar, left after wide stalling, encounters low value of induced stress in comparison to that over the centre of the stooks formed after splitting and stoking of the original pillar. Further, due to triaxial state of loading condition, the effective bearing capacity of a pillar is comparatively more than a number of stooks of the equivalent area (Sheorey et al., 1987). In fact, wide stall simply replaces the four stooks of conventional splitting and stooking by one pillar of equivalent area.

4.1 Important Considerations

With the Wide Stall Method, widths of the existing galleries are increased in a particular fashion to improve coal recovery leaving relatively bigger pillars (in comparison to stooks). Wide Stall formation accommodates the existing galleries of a

[3] A program developed by Crouch Research, Inc., 42 Island road, St. Paul, Minnesota 55127, USA

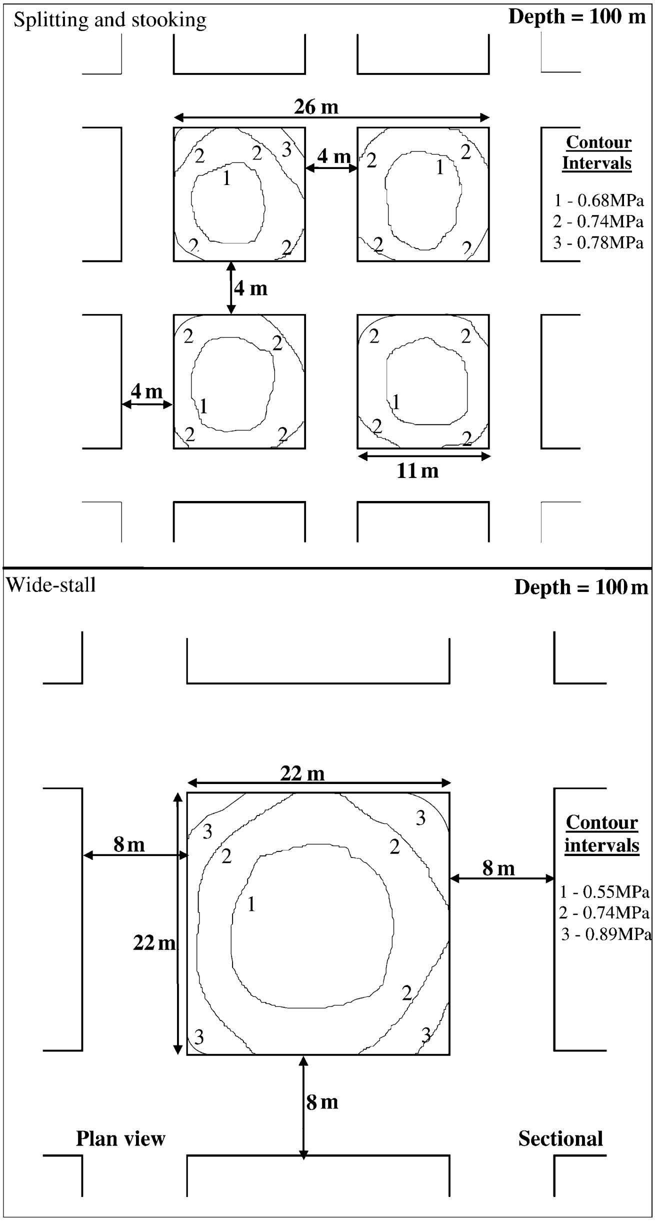

Fig. 7. Boundary element modeling-based contour of mining-induced stress over stooks and a left-out pillar of wide stall

developed coal seam as well as improves recovery and safety of the ultimate mining structure in comparison to the conventional method. First field trial of this method was successfully done with hydraulic sand stowing of widened stalls (Singh and Singh, 1999). The sand stowing was adopted not only to provide a base for the upper lift working but to minimise the chances of pot holing and subsequent weathering of the exposed pillar surfaces. Side thrust and confinement provided by the stowing is considered to improve the strength of the resultant coal pillars.

Recently, two successful field trials of this method without hydraulic sand stowing were undertaken at two different sites. On the basis of different laboratory and field investigations associated with the field trials, three essential considerations for successful adoption of Wide Stall method are:

- thickness of inter burden between the surface/subsurface feature and coal seam should be of the range of 40–100 m,
- overlying roof strata should have rock mass rating[4] (RMR) (CMRI Report, 1987) classes I and II and
- safety factor of the remnant pillar must be above 1.5, preferably 2.

4.2 Support Requirement

Although the presence of a competent immediate roof is an important requirement of WSM, widening of the galleries will increase the chance of roof instability. RMR is used to evaluate the competency of roof strata (Table 2) and is used to calculate rock load under freshly exposed roof of a gallery by the empirical relationship:

$$R_l = 9810Bd(1.7 - 0.037RMR + 0.0002RMR^2) \tag{6}$$

where R_l is rock load in N/m^2, B is gallery width (roof span) in m and d is mean rock unit weight in N/m^3.

This relationship is valid up to 4.2 m gallery width only while wide stall is supposed to have, relatively, wider galleries. To estimate support density, Wilson (1983) considered the rock load of the strata buckled after drivage of gallery, which is given as:

$$\text{Rock load } (Pr) = \left[\frac{2452.5B}{4\tan\phi}\right]\gamma\,\text{N/m}^2 \tag{7}$$

where

B = width of the gallery, m
γ = dry unit weight of roof rock, N/m^3
ϕ = the angle of break to the vertical being the same as the angle of internal friction.

Table 2. Geomechanical classification of roof rock mass (after CMRI, 1987)

RMR	Class	Description
0–20	V	very poor
21–40	IV	poor
41–60	III	fair
61–80	II	good
81–100	I	very good

[4] For a roof stratum of different RMR class, wide stall method can be practised in conjunction with comprehensive roof support; preferably by rock mass reinforcement technique

Recent wide stall practices have adopted this relationship for support density estimation without problem. Conventional supports like wooden/pit props were utilised in the beginning of the experiment. But, later on, different rock mass reinforcement techniques like full column roof/cable bolting were found more suitable to arrest the local roof deformation and movement of the exposed roof above widened galleries. The length of the bolts was estimated through assessment of height (t) of the disturbed strata over the widened galleries, which is given as:

$$t = \frac{B}{2\tan\phi} \tag{8}$$

Different *in situ* pull tests of the full column grouted bolts showed variation in the critical bond length (Pakalnis et al., 1994) of a grout with change in the nature of the strata. Although a systematic study is yet to be conducted in this regard, the critical bond length of the adopted grout (generally being used in industry), varied from 0.8 to 1.2 m for different coal measure formations. Keeping this variation in mind, the length of the reinforcement was always kept 1.2 m more than the value of the height (t) of the disturbed strata over the widened galleries. This procedure of reinforcement length estimation was successfully applied at different sites to control movement of roof strata over widened galleries. It is to be noted here that our practical experience in the field found no difficulty with the above norms for the cable length estimation to support wide stalls. However, the European norms (Wilson, 1983) for support planning of a depillaring/longwalling face were, generally, found not suitable (Singh, 1999) for the Indian coal mines due to a change in caving characteristics of overlying strata because of geological reasons.

4.3 Time-Dependent Weathering

If wide stalling is done without stowing, the long-term stability of the ultimate pillar may be reduced due to time-dependent spalling of the pillars. The spalling proceeds at a steady rate but the rate of spalling varies from place to place and has a wide range of variation. Further, the intensity of spalling mainly depends on three factors (Salamon et al., 1998): environmental conditions, composition of coal and magnitude of mining-induced stresses acting over the pillar. If the coal mass contains certain clay minerals or a band of clay material, swelling of the exposed coal skin is observed in the presence of a humid environment. Here, the swelling of pillar skin generally takes place in a perpendicular direction to the pillar side.

The ensuing tensile strain may cause the affected skin to be peeled off, exposing fresh coal surface and the process keeps repeating. In the presence of such weathering, the effective size of the pillar reduces over time, ultimately, causing a drop in the safety factor and can initiate failure of the pillar. For higher percentage of extraction with wider galleries around the pillars as is the case of WSM, this type of spalling is a serious issue, as the fallen coal from neighbouring pillars will form independent pile (Fig. 8), and will not be in a position to provide confinement to the pillar. The observed rate of spalling for a coal mass without clay minerals is almost zero whereas the reported high rate of time dependent deterioration is up to 0.85 m/year (Salamon et al., 1998) for a coal containing different bands of clay minerals.

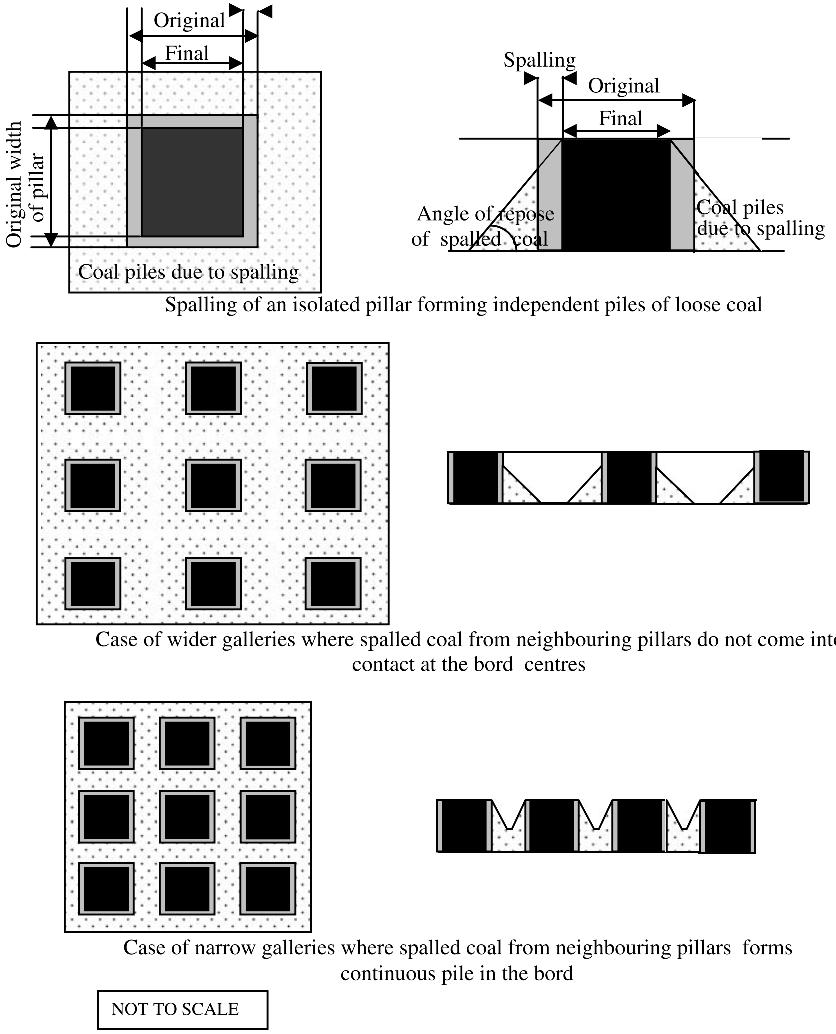

Fig. 8. Development of side confinement to a pillar from spalled coal for different gallery widths (after Salamon et al., 1998)

Experience gained from underground inspection of different coal seams standing on pillars for long term stability assessment showed some side spalling (CMRI Report, 2000) of pillars due to the presence of clay bands in the coal mass. These spallings in the pillars were all along the level drivage only. In fact, due to favourable gravitational condition, the deeper side of the pillars (along the level drivage) experienced the major spalling while the spalling was much less along the two dip-rise sides of the pillar and was almost negligible along the rise side of the pillar. Observed average depth of spalling along the deeper side of pillars was 3.0 m, which occurred over a time period of 15 years. There was a prominent localised clay band of thickness varying between 0.5 and 0.3 m in the coal seam at around 2 m height from the floor of the seam.

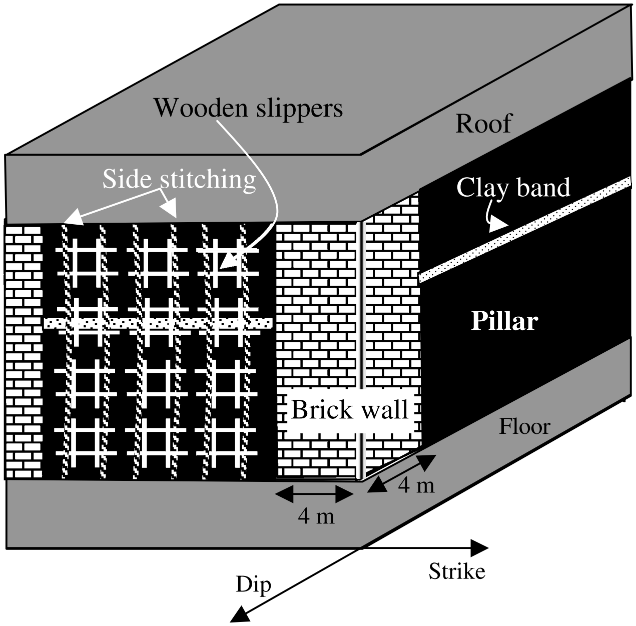

Fig. 9. Scheme of side stitching and brick walling to control pillar size dilution due to time-dependant weathering

The ultimate pillar, after widening of these galleries in the absence of stowing, needed to be side reinforced to prevent the time dependent spalling due to the presence of the clay band. A successful scheme adopted to support the ultimate pillar is shown in Fig. 9. At both the corners of a pillar (deeper side) a brick wall (38 cm) of L shape was erected and the gap between the wall and side of the pillars was completely filled with stone boulders. The rest of the exposed portion of the pillar along the level drivage (deeper side) was side stitched by haulage ropes and eye bolts. At least 2 m length of the rope was grouted inside roof and floor of the seam. Field experience supported skin-to-skin placement of wooden slippers inside the stitched ropes to achieve better confinement over the side of the pillars by the stitching.

5. Case Studies

Field investigations were conducted during successful field trial of WSM at three different sites, namely: (a) East Bhugatdih colliery, (b) Chirimiri colliery, and (c) Umaria colliery. Details of the first field study have already been reported (Singh and Singh, 1999) but are discussed here also for comparison purpose only. This WSM is adopted for regular production from other panels of these three mines after success of an experimental panel at each mine. East Bhugatdih and Chirimiri collieries adopted this method with and without stowing, respectively, to optimize recovery from thick[5] seams.

[5] To be a thick seam in India, thickness of the coal bed should be more than 4.8 m

Table 3. Relevant details of different coal mines that adopted wide stall mining

Parameters	Colliery		
	East Bhugatdih	Chirimiri	Umaria
Depth cover (m)	110	50	65
Seam thickness (m)	17	8.4	3
Development height (m)	3.2	3 (along floor)	3
Extraction height (m)	full (in two sections*)	full	full
Gallery width (m)	3.6	4	4
Stall width (m)	9.0	6	6.5
Treatment of mined out area	stowed	unstowed	unstowed
Ultimate recovery (%)	41.7	47	59

* An intact coal parting of 3 m thickness was left between the two sections and each section consisted of two lifts.

The surface area of East Bhugatdih consisted of a township while that of Chirimiri consisted of green vegetation (fragile ecology). Recovery optimisation from a developed coal seam of normal thickness at Umaria colliery also adopted WSM to restrict chance of water discharge from an overlying sub-surface aquifer. The geo-mining details of the three mines are given in Table 3. Coal seams of the three sites were standing on pillars with safety factor more than 5. The scope of optimal recovery of coal locked in oversize pillars at these three sites led the field trial of wide stall. Borehole sections of overlying strata of these three mines are shown in Fig. 10.

5.1 East Bhugatdih Colliery

At East-Bhugatdih colliery, 17 m thick VII/VIII seam was fully developed in two sections; 3.0 m thick bottom section along floor and 2.4 m top section leaving 6.4 m coal parting between the two sections and 5.0 m coal in roof. Total recovery attained by pillar formation (30 × 30 m, centre to centre) in two sections, having 3.6 m wide gallery, was 7.4% only. Experimental panel consisted of 25 pillars at an average depth of cover of 110 m and was completely free from geological disturbances. In addition to the surface objects the optimisation of recovery from this coal seam also faced problems due to overlying developed X seam at 43 m height (Fig. 10).

Widening of galleries around the two undersize pillars of the panel was not possible due to long-term safety consideration of the pillars. The seam was already developed in two sections so the optimisation of recovery was planned accordingly in two sections. As per the thickness and positions of the available working horizons in the seam, two slices of equal heights were planned for each section. Working was done in ascending order from the bottom slice keeping slices heights of bottom and top sections equal to 3.2 and 3.6 m, respectively, and leaving an intact coal bed of 3 m thickness between the top and bottom sections (Fig. 11).

The stall formation at East Bhugatdih involved widening of 3.6 m wide development gallery to 9 m, which was possible by taking a 2.7 m wide strip on both sides of an existing heading. Because of blasting constraints and rehandling of the supports, it was decided to operate a 5.4 m wide wing face on one side of the gallery. Under this scheme, extraction from a pillar (30 × 30 m) involved formation of two wing faces,

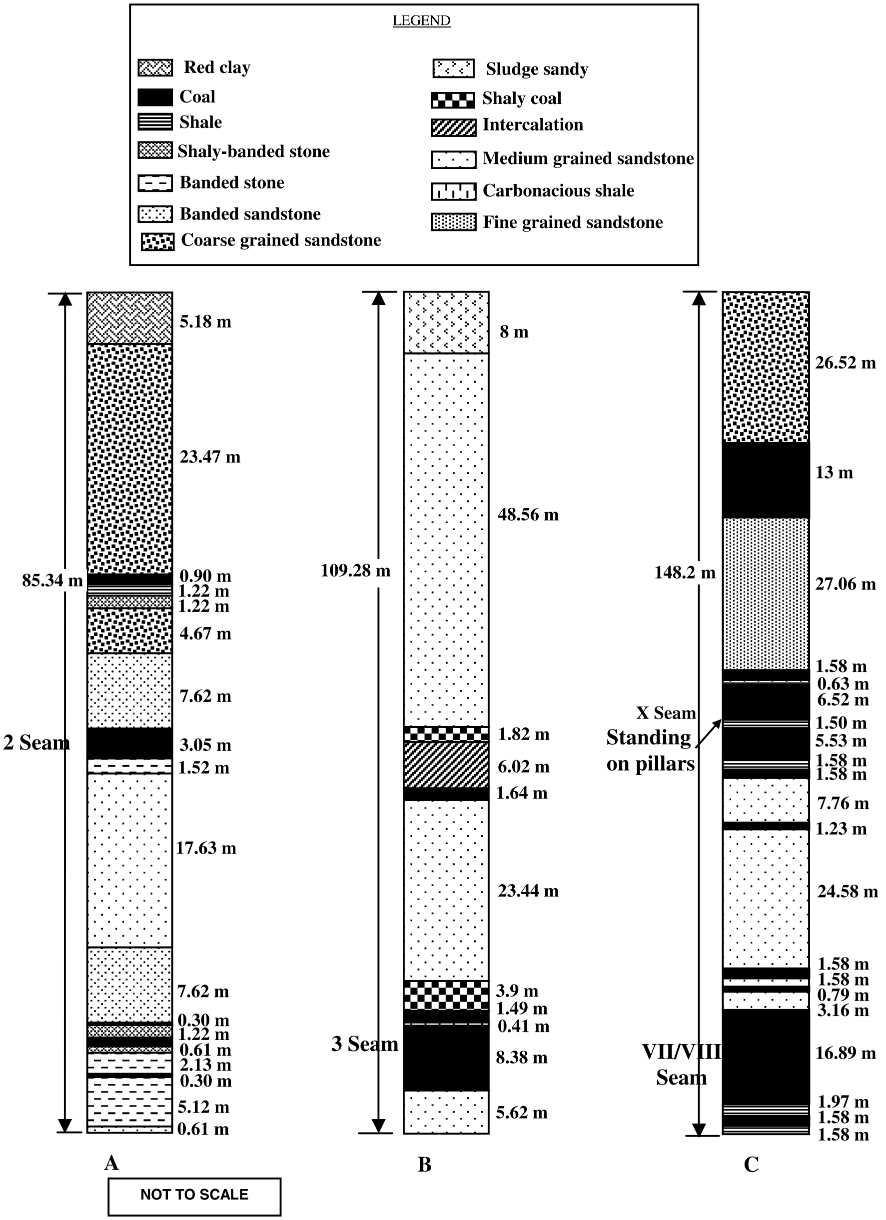

Fig. 10. Borehole section of overlying strata at (A) Umaria colliery (B) Bartunga Hill Mine and (C) East Bhugatdih colliery

each of 5.4 m width (maximum), in form of "L" block to reduce the ultimate size of the pillar to 21×21 m.

Successful application of this method at East Bhugatdih colliery provided nearly 42% coal from a multi-section developed 17 m thick coal seam without endangering

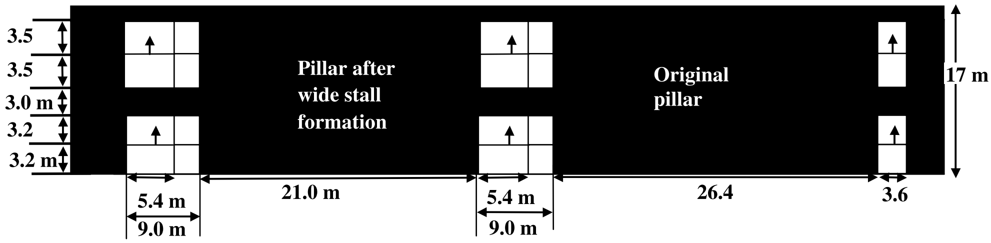

Fig. 11. Dimensional information and sectional view of wide stall mining at East Bhugatdih colliery

the surface and subsurface structures. Strata movement monitoring in and around the panel continued for three more years after closure of the panels. Readings of strata movement monitoring did not show any ground instability in and around the panel after the working.

5.2 Chirimiri Colliery

8.4 m thick No. 3 seam of Chirimiri mine is extensively developed and standing on pillars. Mostly the development is made along floor with a gallery height of 2.5–3 m, leaving at least 5 m intact coal band along the roof. The life of Chirimiri mine exclusively depends upon underground exploitation of the developed pillars and roof coal band of No. III seam (Table 4). Depillaring with caving is found difficult to be practiced in some portion of the seam where cover thickness was quite small (>100 m). Here, depillaring of the thick III seam was expected to cause severe damage to green vegetation, present over the surface. While stowing of the voids was practically not feasible, mainly, due to unavailability of the stowing materials.

After a detailed analysis of geo-mining conditions of the site and study of physico-mechanical properties of coal and overlying strata, Wide Stall Method was implemented for recovery optimisation from shallow portions of the thick and developed No. III seam. Conventional simple calculations for estimation of width and height of wide stalls (Singh and Singh, 1999) suggested development of the seam along roof, exactly superimposed over the exiting bottom section development (Fig. 12) and leaving a parting of coal, at least, 3 m thick. As per the calculations, developed galleries of the top section were widened to 6 m by taking 1 m thick slice from both sides of the gallery and the working face advanced in conventional diagonal manner.

Table 4. Thickness and reserve of coal seams at Chirimiri (Bartunga hill) colliery

Name of seam	Thickness (m)	Reserve (million ton)	Remarks
Zero	5–12	7.00	present in a patch of the leasehold below hill cap
Local	1.2–2	1.2	working in progress
I	1.5–1.7	3.18	fully developed and partly depillared
II	1.2	4.0	virgin
III	8–10	51.0	standing on pillars
IV	2.5	not known	proved in opencast leasehold only

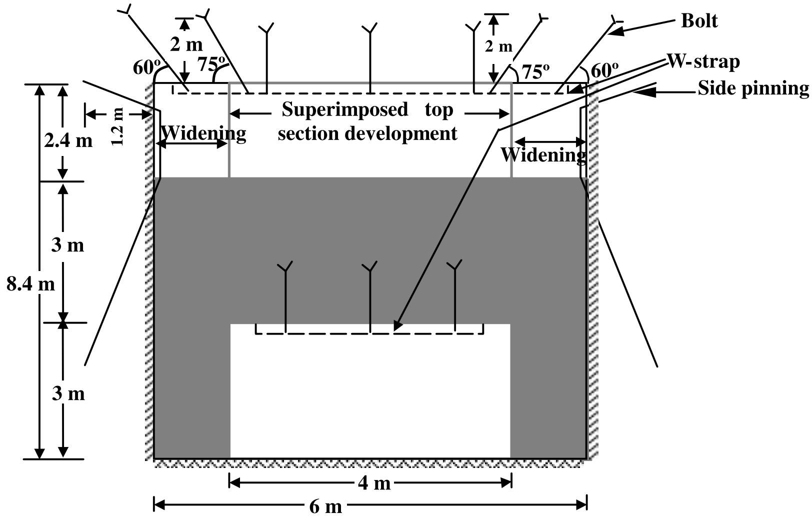

Fig. 12. Dimensional information and sectional view of wide stall mining at No. 3 seam of Bartunga Hill Mine

Roof bolts with W-straps were used to support roof strata over the widened galleries. After completion of widening of top section galleries, similar widening of the bottom section galleries progressed in the conventional depillaring manner. Blasting of the sublevel coal (parting) was done simultaneously during bottom section widening by ring hole blasting technique during retreat (Fig. 13). To strengthen the stability of the heightened pillar after final working, the widened side galleries of top section were side stitched before the ring hole blasting. Nearly 47% coal recovery was

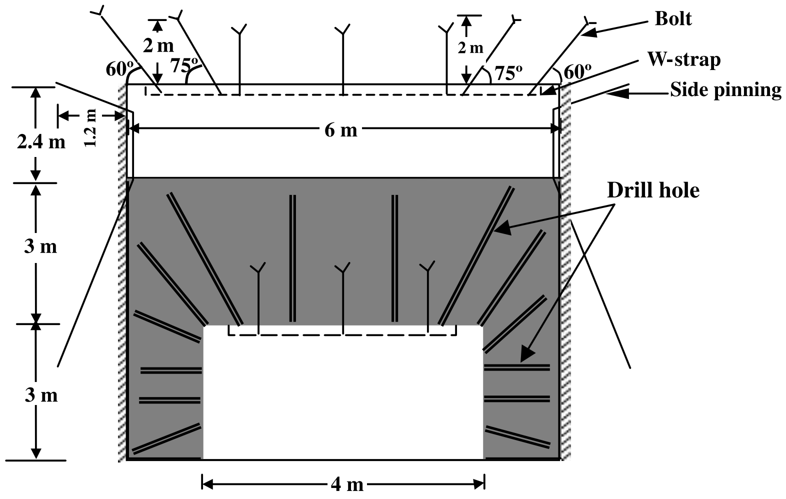

Fig. 13. Blasting of roof and side coal during retreat at Bartunga Hill mine

achieved in the first experimental panel after the wide stalling. A number of panels of the seam lying in shallow cover zone of the mine were extracted without disturbing the surface environment. Strata movement monitoring in and around the wide stall panels of the mine did not show any considerable amount of ground movement.

5.3 Umaria Colliery

Five coal seams (No. I–V) are present in the leasehold area of Umaria colliery. Topmost No. I seam is left virgin due to heavy percolation of water from the roof during an attempt of pillar formation. Seams No. III–V are not workable in the leasehold of Umaria Colliery. No. II seam is the main working seam in the leasehold of the mine. This coal seam is nearly flat and has extensively been developed on pillars to full height as per CMR 1957. Depth of cover of the seam in the leasehold area of the mine varies between 55 and 85 m. Recovery optimisation from No. II seam, standing on pillars, is a major problem due to presence of highly water bearing overlying strata. Depillaring of this seam was not possible due to presence of heavily charged aquifers at 12–15 m height from the seam.

After going through a field and laboratory investigation for optimisation of coal recovery from the developed No. II seam of the mine, CMRI recommended application of WSM. As per the recommendation, the developed galleries of 4 m width were widened to 6.5 m to achieve nearly 59% overall recovery from the seam. Because of blasting constraints and rehandling of the supports, it was decided to operate a 2.5 m wide wing face on one side of the gallery. Under this scheme, extraction from a pillar (14 × 14 m, corner to corner) involved formation of two wing faces, each of 2.5 m width (maximum), in form of "L" block (Fig. 14) to reduce the ultimate size of the pillar to 11.5 × 11.5 m. The mine experienced successful wide stalling in a number of panels without any problem.

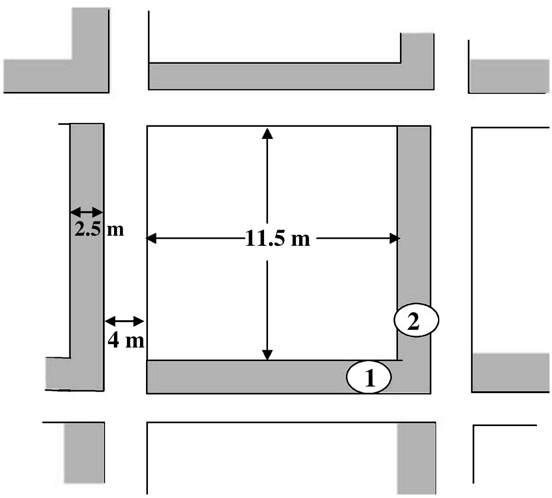

Fig. 14. Plan view of wide stall formation at Umaria colliery

5.4 Strata Movement Study

To evaluate the performance of the stall formation in the field, different parameters like mining-induced stress, roof to floor convergence, load on support, surface subsidence, etc. were monitored during the workings. Depending upon the nature of the roof rock mass and other geo-mining conditions of the site, some variation in local strata movement in and around the working was noticed but the surface movement remained absent during all the observations. The value of mining-induced stress (vertical) increased only during the formation of the stalls but it became constant thereafter. The core of the ultimate pillar was always found to be at, relatively, low value of mining-induced stress. A typical development of mining-induced stress over the ultimate pillar during the wide stalling is shown in Fig. 15. The major part of the induced stress development took place during wide stall formation in and around the instrumented pillar only. Similar nature of variation was observed for roof to floor convergence also. Generally, a small value of roof to floor convergence was observed during the formation of the wide stall (Fig. 16) only. At all the three sites, the roof to floor convergence value ceased after the stall formation and remained almost stable inside the goaf. In fact, depending on the characteristic of the roof strata, the designed widths of stalls and applied support system were found effective for optimisation of recovery from a developed coal seam. Strata movement studies at all the three sites did not give any indication of instability in and around the wide stall formation.

For optimisation of recovery from a thick seam, multi-lift wide stalling was done at East Bhugatdih colliery with hydraulic sand stowing. The stowing was adopted for two main reasons: a) to provide side confinement for the taller pillars and b) to make a floor available for the upper lift workings. However, in the absence of the stowing material, single lift working of a thick seam was done at Chirimiri colliery with the help of rock mass reinforcement. After completion of the superimposed developments along floor and roof, leaving a 3 m thick inter-burden coal parting, the wide stalls of

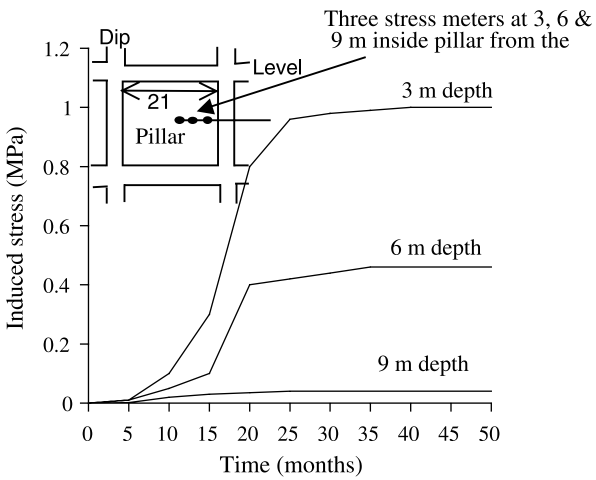

Fig. 15. A typical nature of mining-induced stress (vertical) development over a pillar during wide stall mining in the panel

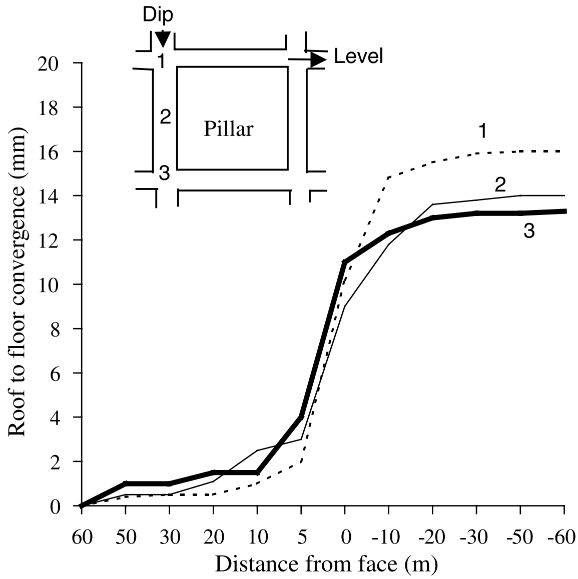

Fig. 16. General trend of roof to floor convergence during wide stall mining in the panel

normal height were formed in top section and the roof strata were reinforced by roof bolts with W-straps. Junctions were additionally supported by rope stitching with eye-bolts. After this the bottom section wide stall was formed and parting coal was won by ring-hole blasting during retreat.

Bottom section working was done below the reinforced roof strata of top section. In fact, before the bottom section working, the sides of the pillar supports were reinforced at its ultimate middle height to improve the stability of the heightened pillars. However, wide stalling in a normal height coal seam did not require any side reinforcement. A coal seam of 3.0 m thickness at Umaria colliery adopted roof-bolting (1.5–2.5 m length) support for wide-stall formation without any problem. The stalls of this mine were left unstowed and were completely filled with water within a couple of months of working. There is a chance of spontaneous heating of a developed coal seam at shallow cover due the presence of natural fissures. Here the filled water arrested the chance of heating and worked as a cover for the exposed coal surface of the seam. The buoyancy pressure of the water also provided some support to the superincumbent strata. Surface subsidence monitoring, done at all the three sites for more than three years after closure of the wide stall panels, failed to notice any considerable ground movement due to the wide stall workings.

6. Conclusions

In India, coal seams below important surface/subsurface objects have extensively been developed on room and pillars due to favourable techno-economic reasons. Formation of pillars gives a maximum 30–35% recovery in a normal height coal seam while the recovery goes down sharply for thicker coal seams. Optimisation of recovery from these coal seams, standing on pillars below surface/subsurface constraints, needs detailed study of the geo-mining conditions of the site.

One way to optimise the recovery is to control the dimension of excavation using a concept termed the non-effective-width of the site. The value of non-effective-width increases with the cover of the coal seam, so different dimension of excavation may be adopted for different cover of the seam if the depth of the seam varies considerably. When the value of non-effective-width (for shallow cover) does not fit for extraction of even single row of pillars then the surface may be affected even if alternate row of pillars is extracted. Here potential of Wide Stall Mining can safely be utilised to optimise the recovery. This method of recovery optimisation has successfully been adopted in the field with different variants of goaf treatment under varying conditions of the sites.

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References

CMR, 1957 (2000): The coal mines regulations (1957): In: Kaku, L. C. (ed.), Lovely Prakashan, Dhanbad, 284.

CMRI Report (2000): Long-term stability of developed workings below railway line at KK1 & KK2 inclines. Dhanbad, 31.

CMRI Report (1987): Geo-mechanical classification of coal measure roof rocks vis-à-vis roof supports. Dhanbad, 125.

Crouch, S. L., Starfield, A. M. (1983): Boundary element methods in solid mechanics (with applications in rock mechanics and geological engineering). George Allen and Unwin, London.

Hoek, E., Brown, E. T. (1980): Underground excavation in rock. The Institution of Mining and Metallurgy, London, 527.

Hudson, J. A., Harrison, J. P. (1997): Engineering rock mechanics: an introduction to the principles. Elsevier Science Ltd., Oxford, UK, 444.

Loui, J. P., Sheorey, P. R. (2002): Estimation of non-effective width for different panel shapes in room and pillar extraction. Int. J. Rock Mech. Min. Sci. 39, 95–99.

Mandal, P. K., Dubey, B. K. (1999): An eco-friendly underground mining method – two case studies. Singh, T. N., Gupta, M. L. (eds.), Proc., Int. Symp. on Clean Coal, New Delhi, India, 2003–2219.

NCB (National Coal Board) (1975): Subsidence engineers handbook. NCB, Hobard House, London, 1966, Rev., 538.

Pakalnis, R., Peterson, D. A., Mah, G. P. (1994): Glass fiber cable bolts – an alternative. CIM Bull. 87(976), 53–57.

Salamon, M. D. G., Ozbay, M. U., Madden, B. J. (1998): Life and design of bord-and-pillar working affected by pillar scaling. J. South African Ins. Min. Metall. 135–145.

Saxena, N. C., Kumar, B., Singh, B. (1989): Subsidence research in India. Int. Symp. Land Subsidence. Dhanbad, India, 87–102.

Sheorey, P. R. (1992): Pillar strength considering in situ stresses. Information circular (IC) 9315, United States Departments of the Interior, Bureau of Mines, 122–127.

Sheorey, P. R., Das, M. N., Barat, D., Prasad, R. K., Singh, B. (1987): Coal pillar strength estimation from failed and stable cases. Int. J. Rock Mech. Min. Sci. Geomech. Abstract 24, 347–355.

Sheorey, P. R., Singh S. K. (1996): Non-effective width of extraction and goaf pillar method for subsidence control. Second National Conf. on Ground Control in Mining, Calcutta, India, 49–56.

Sheorey, P. R., Lui, J. P., Singh, K. B., Singh, S. K. (2000): Ground subsidence observations and modified influence function method for complete subsidence prediction. Int. J. Rock Mech. Min. Sci. 37, 801–818.

Sheorey, P. R., Mohan, G. M., Sinha, A. (2001): Influence of elastic constants on the horizontal in situ stress. Int. J. Rock Mech. Min. Sci. 38, 1211–1216.

Singh, K. B. (2000): Causes and remedial measures of pothole subsidence due to coal mining. J. Sci. Ind. Res. 59, 280–285.

Singh, R. (1999): Mining methods to overcome geo-technical problems during underground winning of thick coal seams – case studies. T. Inst. Min. Metall. (IMM), UK 108, A121–A131.

Singh, R., Singh, T. N. (1999): Wide stall mining for optimal recovery of coal from a multisection developed thick seam under surface features. Int. J. Rock Mech. Min. Sci. 36(2), 155–168.

Singh, T. N. (1999): Clean coal initiatives. Singh, T. N., Gupta, M. L. (eds.), Proc., Int. Symp. on Clean Coal, New Delhi, India, 1–16.

Singh, T. N., Prasad, D., Rafiqui, M. A. (1992): Wide stall mining – a method for partial extraction of thick seam underneath surface structures. Singh, T. N., Dhar, B. B. (eds.), Proc. Int. Symp. on Thick Seam Mining. CMRI, Dhanbad, India, 367–380.

Wilson, A. H. (1983): The stability of underground workings in the soft rocks of the coal measures. Int. J. Min. Eng. 1(2), 91–187.

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