Web and barrier pillar design for Highwall Mining at OCP-II of SCCL, India

John P. Loui (Central Institute of Mining and Fuel Reseach, Regional Center, Nagpur, India)
P. Palroy, A. Kushwaha (Central Institute of Mining and Fuel Reseach, Dhanbad, India)
U. M. Rao Karanam (Indian Institute of Technology, Kharagpur, India)

1. INTRODUCTION

Opencast coal mining in India was started 20 to 30 years ago in large scale, but some of them are reaching their final pit limit in the near future. In many cases, the existence of surface features such as residential areas limits the expansion of open pits. Some amount of coal will always remain locked up between the open pit highwall and the adjacent underground mine workings.

Highwall Mining Method is a remotely operated mining technology yet to be introduced in India. This is a highly economical and productive method to extract coal from surface mines which has reached the pit limits. The method comprises of extracting coal from a series of parallel entries driven in the coal seam from the face of the highwall. These entiries will be unmanned, unsupported and unventilated. A rate of production of 500T/hour is achievable by this method, thus making the entire mining operation highly economical.

At Ramagundem OCP-II opencast mine of Singareni Collieries Company Limited (SCCL), Advanced Mining Technology Private Limited (AMT) has been contracted to extract the remnant coal within the mine boundary by underground Highwall Mining Method. The highwall extractions are planned with ADDCAR Highwall Mining Systems, USA. This could be the first Highwall Mining operation in the country. The seams existing within the property include Seam IV, Seam III, Seam IIIA, Seam IIIB, Seam II & Seam I, in ascending order. Out off the above six seams IIIB seam is declared unworkable due to insufficient thickness. Hence five seams are targeted for Highwall Mining, viz. Seam IV, Seam III, Seam IIIA, Seam II and Seam I. The major coal reserve is locked up in Seam IV and Seam III occurring in close proximity separated by a parting of 4-5m of sandstone. At places this parting is reduced to less than 3m, and at a very few locations III & IV Seams occur as one. General dip of the coal seams is 1 in 4.2 and maximum length of entries would be 350 m from the highwall. The estimated coal recovery would be over one and half million tons with a recovery rate of around 35 to 40% from insitu.

About 900m length of the highwall at the pit bottom is exposed and available for highwall mining operations. The extent of the highwall mining block is defined considering a minimum of 20m barrier from the OC-II mine boundary. The highwall has an overall slope angle of about 47^{o}. Therefore, the bottom most Seam IV will have the highest mineable reserve and the top most Seam I will have the least. From rock mechanics point of view, the key issue concerning any Highwall Mining will be the optimum design of intervening web pillars between adjacent entries.
The proposed mining block with a section of the open pit highwall showing the exposed seams is as given in Fig. 1.

The major points to be considered from geotechnical perspective towards the highwall mining operations of all the five workable seams may be as follows:

1. A suitable sequence of extraction of the seams, ensuring maximum extraction from all the workable seams and minimum damage to the overlying seams
2. An optimum extraction strategy for each seam with a combined strategy for III & VI Seams
3. Design of web pillars and barrier pillars for each panel in all the workable seams, ensuring optimum recovery and protection of upper seams

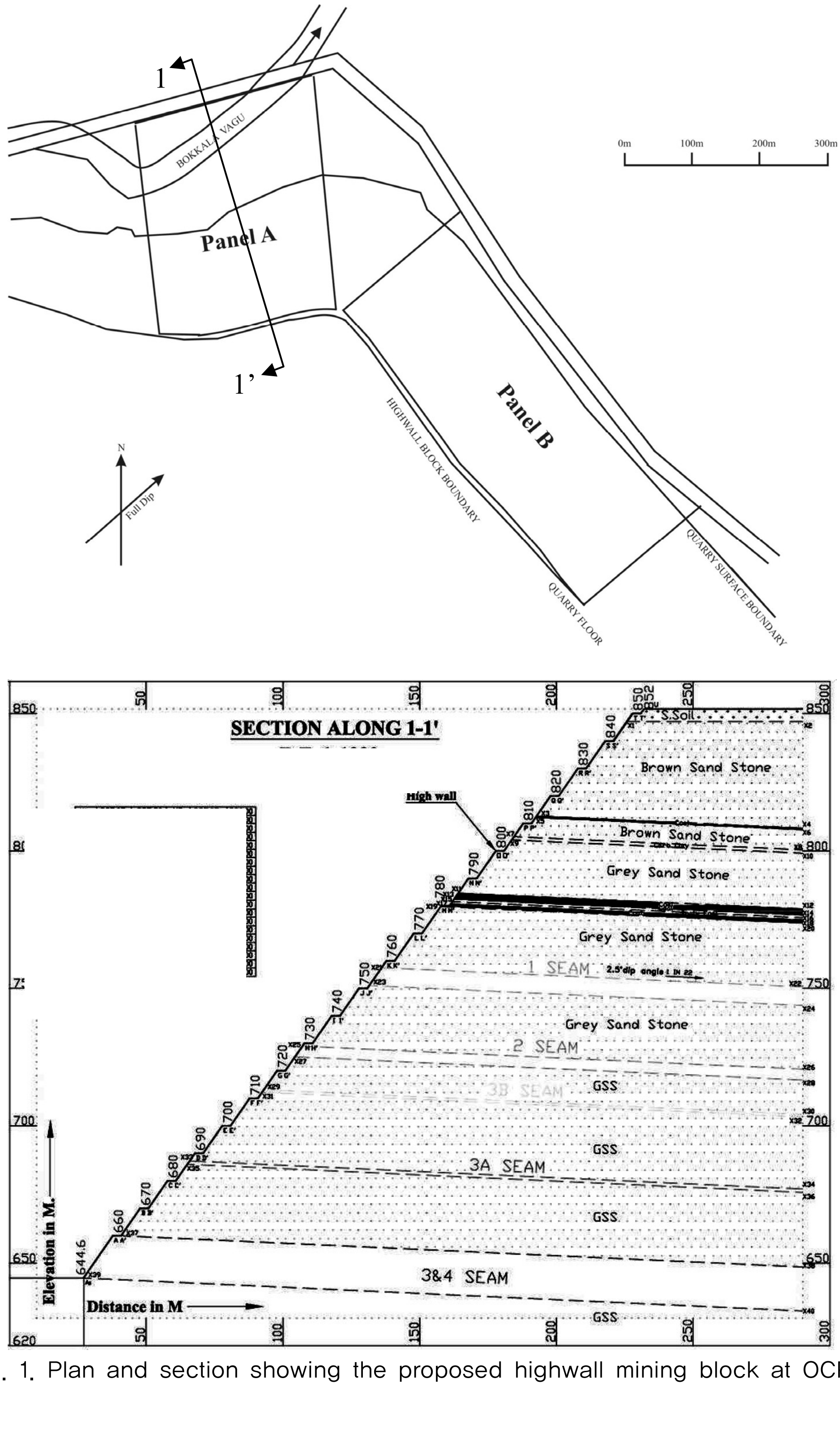

Fig. 1. Plan and section showing the proposed highwall mining block at OCP-II

The above geotechnical aspects have been dealt with in this paper with the help of empirical pillar design approach supported by numerical modeling studies using *FLAC3D* software of ITASCA Consultancy Groups, USA.

2. GEOTECHNICAL DATA

Pertinent geotechnical data for the design of OCP-II Highwall Mining has been obtained from SCCL and AMT. Depth of cover, seam thickness and the parting thickness of all the workable seams are given in Table 1.

Table 1. Seam details

Seam	Depth of cover, m	Thickness, m	Parting, m
I	95-154	5.2-6.7	---
II	112-182	3.1-4.0	21-29 with Seam I
IIIA	155-229	0.9-1.8	31-47 with Seam II
III	184-255	11-12.2	24-28 with Seam IIIA
IV	199-270	3.7-4.1	4-5.6 with Seam III

The physico-mechanical properties of the seams and their respective immediate roof are given in Table 2. These properties were tested earlier by National Institute of Rock Mechanics (NIRM test report, 2007). The values given in Table 2 are used for the current design.

Table 2. Physico-mechanical properties of the seams and immediate roof

Strata	$\sigma_c\ (kg/cm^2)$	$\sigma_t\ (kg/cm^2)$	$E\ (kg/cm^2 \times 10^5)$	ν
I Immed. Roof	113	9	0.50	0.50
I Seam	365	24.80	0.274	0.285
II Immed. Roof	-	-	-	-
II Seam	340	24.27	0.26	0.26
IIIA Immed. Roof	366	-	1.01	0.36
IIIA Seam	395	22	0.35	0.31
III Immed. Roof	251	-	1.01	0.42
III Seam	415	27	0.32	0.34
IV Immed. Roof	315	-	1.07	0.43
IV Seam	414	23	0.34	0.33

The rock mass parameters used for strength reduction in the numerical modelling studies are as given in Table 3.

Table 3. Rock mass properties of immediate roof

Parameter	I Seam		II Seam		IIIA Seam		III Seam		IV Seam	
	Low	High	Low	High	Low	High	Low	High	Low	High
RQD (%)	40	100	75	97	60	80	48	52	48	52
RMR	33	74	40	74	38	79	33	70	33	65
Q	0.29	28	0.64	28	0.51	49	0.29	18	0.29	10

3. STRATEGY FOR EXTRACTION

The final pit slope has already been reached, indicating the end of all the possible open cast mining operations; the pit limit on the surface has also reached the limit of the mine, exposing all the seams as outcrops on the final pit slope. Further benching is not possible in the 47^o pit slope and hence the Highwall Mining can only progress upward from the bottom seam IV to the top most Seam I. After the extraction of Seam IV it will be necessary to fill the pit bottom till the horizon of Seam III, forming a platform for its extraction, and so on and so forth.

For extraction of seams in ascending order it is necessary that the left out web pillars would ensure protection of the upper seams for the period they are required. Therefore, web pillars are to be designed for medium or long-term stability.

The web pillars designed for medium or long-term stability should also take care of the highest depth at which the pillars would exist. The end effect of the cuts at the boundary may also be studied using numerical modeling to arrive at the maximum effective depth.

For seams at the deepest horizon, viz. Seam III and Seam IV, the depth variation is quite wide, which may result in over-designed web pillars to a larger extent of penetration depth. In order to maximize the recovery, alternate long and short penetration cuts may also be designed in such a way that the minimum required safety factor is achieved through out the length of the web pillars.

Since the Seams III and IV are occurring in contiguity, a combined web pillar design needs to be followed for the two seams, preferably by maintaining verticality of extraction with pillar columnization.

On the basis of earlier mining data, the Mk3 Highwall Mining Guidance System, incorporating HORTA inertial navigation claims to have accuracy, in terms of the off-track deviation, of less than 0.2% of the penetration depth, i.e. a maximum of 20cm of hole deviation for every 100m of penetration depth (Addcar, 2004). This aspect will be considered while designing the web and barrier pillars.

4. Elastic numerical modelling studies for load estimation

There shall be three factors affecting the maximum vertical stress acting on the web pillar as given below:

a) The “end effect” at the maximum depth zone facing the solid boundary
b) Effect of the highwall slope
c) The web and cut widths

Analysis of vertical stress acting on the web pillar has been conducted using three-dimensional elastic modeling in FLAC3D software of ITASCA. The results of elastic modeling revealed the following aspects:

1) The maximum vertical stress acted upon the elements lying about 20m from the boundary.
2) The maximum vertical stress magnitude is found to be roughly 90% of the maximum tributary area load corresponding to the maximum depth.

The above findings are made use for the evaluation of maximum load on the web pillar, to be used in the empirical calculation.

5. Empirical web pillar design

Web pillars are designed for III and IV Seams combined, IIIA Seam, II Seam and I Seam. The methodology adopted for the empirical design is as given below.

5.1 Estimation of pillar strength

The estimation of pillar strength is done using CIMFR pillar strength formula (Sheorey, 1992), which reads as

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

where

S	= strength of the pillar, MPa
σ_c	= strength of 25mm cube coal sample
h	= working height, m
H	= depth of cover, m
W_e	= equivalent width of pillar, m
	= 2W for long pillar
W	= width of web pillar, m

5.2 Pillar load estimation

Load on pillars can be estimated using tributary area method, which reads as:

$$P = \frac{\gamma\, H\, (W + W_c)}{W}$$

where

P	= load on web pillar, MPa
γ	= unit rock pressure (0.025 MPa/m)
W_c	= web cut width, m

5.3 Safety factor

Safety factor of the pillars can be calculated using the above equations as given below:

$$S.F. = \frac{\textit{Strength of web pillar}}{\textit{Load on web pillar}} = \frac{S}{P}$$

The CMRI pillar strength equation has been developed over a couple of decades after analysis of a large number of pillar stability observations from a gamut of Indian mining scenarios. On the basis of past experiences from Indian coalfields it has been observed that a pillar safety factor of more than 2.0 is long-term stable, i.e. for many decades. A safety factor between1.5 to 2.0 may be taken as medium-term stable, stable for a few years. If the safety factor of the pillar is 1.0, it may be treated as short-term stable, with a standup time of a few weeks or a month.

6. Extraction of III & IV Seams

The following points are kept in mind while designing web pillars for these two seams:

1) Maintain columned pillars in III & IV Seams
2) Design web for safety factor 2.0 in IV seam, which will form the base
3) Design web pillar in III Seam, maintaining verticality with IV Seam, but with 1.5 safety factor
4) Extraction of IV Seam to full height (4.0m)
5) Extraction of III Seam in two passes to a height of 8.0m
6) Positioning of the two-pass extraction in III Seam as high as possible after leaving 0.5-1.0m coal in the III Seam roof, thus maximizing the parting between III & IV Seams
7) Due to the wider variation in depth, alternate short and long hole extraction pattern to be designed to maximize the recovery as shown in Fig. 2.

(a)

(b)

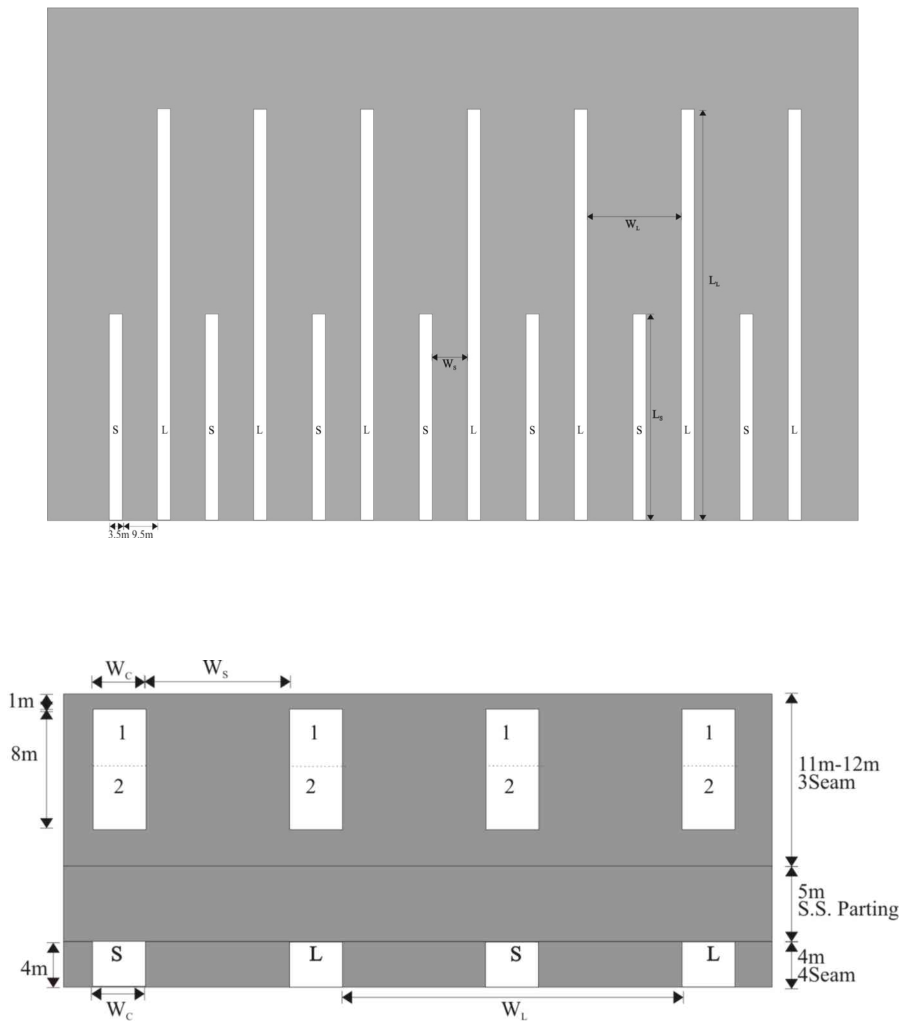

Fig. 2. Schemes for extracting III and IV Seams (a) plan (b) vertical section

The design which gives maximum recovery as per the above strategy will be as given in Table 4.

Table 4. Web pillar design for safety factor 2.0 in IV Seam and safety factor 1.5 in III Seam

Seam (ht. ext., *h*)	**Panel 4-A / Panel 3-A**					**Panel 4-B / Panel 3-B**				
	Long holes		**Short holes**		**% ext**	**Long holes**		**Short holes**		**% ext**
	Avg. length L_L	**Web width W_L**	**Max. length L_S**	**Web width W_S**		**Avg. length L_L**	**Web width W_L**	**Max. length L_S**	**Web width W_S**	
IV (4m)	345m	13.1m	115m	4.8m	25.7	225m	14.5m	135m	5.5m	26.8
III (8m)	340m	13.1m	60m	4.8m	24.8	220m	14.5m	67m	5.5m	25.4

7. Extraction of IIIA Seam

Only long hole extractions are proposed in IIIA Seam. Further, the extraction is proposed only in Panel IIIA-B. The optimized design and the recovery is given in Table 5.

Table 5. Web pillar sizes designed for safety factor 2.0 in IIIA Seam

Full length holes in Panel 3A-B		**(ht. ext., *h*)**	**% ext**
Avg. length L_L	**Web width W_L**	1.8m	41.2
190m	5.0m		

8. Extraction of II Seam

II Seam has a maximum thickness of 4.0m and can be extracted in Panel-A and Panel-B. Alternate short and long cuts are designed in this seam for achieving maximum recovery. The design for this seam for a safety factor of 2.0 is as given in Table 6.

Table 6. Web pillar design for safety factor 2.0 in II Seam

Panel 2-A					**Panel 2-B**				
Long holes		**Short holes**		**% ext. (ht. ext., *h*)**	**Long holes**		**Short holes**		**% ext (ht. ext., *h*)**
Avg. length L_L	**Web width W_L**	**Max. length L_S**	**Web width W_S**		**Avg. length L_L**	**Web width W_L**	**Max. length L_S**	**Web width W_S**	
275m	8.1m	35m	2.3m	34.0 (4.0m)	156m	8.5m	40m	2.5m	36.6 (4.0m)

9. Extraction of I Seam

Seam-I is the top most seam with no other extractable seams above and surface features to be protected from subsidence. The web pillars in this seam are designed only for short-term stability; say a minimum safety factor of 1.0. All the extractions are to the full length possible. However, this requires leaving barrier pillars at regular intervals. Following steps were taken while designing barrier pillars in Seam-I to ensure arresting of cascading web pillar collapse.

1) Barrier pillars should be able to take additional load from the excavated portion on both sides assuming complete collapse of the web pillars.
2) Wilson's approach is used to find the abutment loading on to the barrier pillars from the caved goafs. This approach is based on the theory that the full cover pressure in the goaf occurs at 0.3x*H* distance from the edge of the barrier pillar.
3) The barrier pillars should have a minimum safety factor of 2.0, when the web pillars on one side of the barrier are fully crushed forming a caved zone; and a minimum safety factor of 1.5 when both the sides are caved.
4) The spacing between the barrier pillar should be such that the width of each sub-panel should not exceed the critical width resulting in the occurance of full cover pressure in the middle of the sub-panel, say $W_p < 0.6 \times H$.

With the above points, the following design was arrived at, as given in Table 7.

Table 7. Web pillar and barrier pillar design for Seam I extractions

Panel 1-A						Panel 1-B					
Web pillar		**Barrier Pillar**			**Over all % ext. (ht. ext., *h*)**	**Web pillar**		**Barrier Pillar**			**Over all % ext. (ht. ext., *h*)**
Avg. length L_L	**Web width W_L**	**Barrier width W_B**	**Sub-panel width W_P**	**No. of web cuts N_C**		**Avg. length L_L**	**Web width W_L**	**Barrier width W_B**	**Sub-panel width W_P**	**No. of web cuts N_C**	
250m	3.6m	15.0 m	75.5m	11	41.0 (4m)	138m	3.9m	17.0 m	92.3m	13	39.9 (4m)

A schematic plan of the proposed extraction pattern in Seam I is given in Fig. 3.

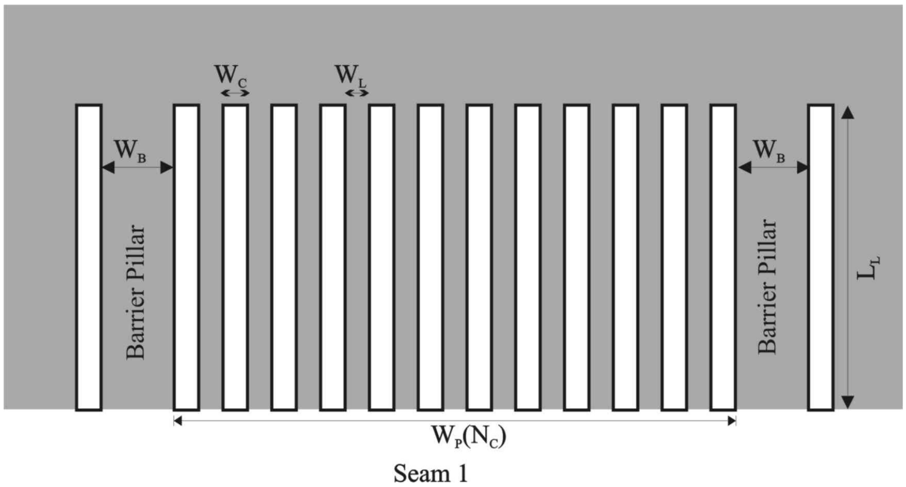

Fig. 3: Plan showing the scheme for extracting Seam I

10. Numerical estimation of pillar strength

The web and barrier pillar design in the current study is primarily based on the empirical design approach as discussed above, owing to the greater confidence in the pillar strength equation developed over a couple of decades of observation in a gamut of Indian mining scenario. However, the empirical design does not really account for aspects such as behaviour of columnized and staggered pillar configurations in close proximity.

The scope of the numerical pillar strength modelling study is limited to a comparative analysis of the above said pillar configurations in III and IV Seams with those of independent workings in III and IV Seams. The peak strength values obtained from the numerical modelling exercise is therefore not directly used in the design but used for comparison with independent pillar strength values. Nevertheless the results will supplement the empirical design by accounting for the variations in pillar configuration for III and IV Seams combined extractions.

FLAC3D software provide for elasto-plastic analysis of rock excavations with strain-softening material model using the linear Mohr-Coulomb failure criterion (FLAC3D manual, 2005; Mohan et al., 2001). The input parameters used for the strain-softening models are as given in Table 8.

Table 8. Input parameters used in the strain-softening models

Rock type	τ_{sm}, MPa	ϕ_{0m}, deg	σ_t, MPa	E, GPa	ν	Density, kg/m^3	Dilation angle
Coal	1.6	29	0.63	3.33	0.25	1500	0
Sandstone	3.2	34	1.3	10.0	0.25	2500	0

The residual values for cohesion and friction angle are then taken as:

$\tau_{sm\,(residual)} = 0$
$\Phi_{0m\,(residual)} = \Phi_{0m} - 5\,^{o}$

The variation of cohesion and friction angle with respect to shear strain are taken as given in Table 9.

Table 9. Change in τsm and Φ0m with shear strain

Shear strain	Cohesion (τ_{sm}), MPa	Friction angle Φ_{0m}), deg.
0.000	τ_{sm}	Φ_{0m}
0.005	τ_{sm} /5	$\Phi_{0m} - 2.5$
0.010	0	$\Phi_{0m} - 5$
0.050	0	$\Phi_{0m} - 5$

Estimation of pillar strength has been made in a way analogous to that of laboratory estimation of uniaxial compressive strength under servo-controlled testing conditions.

The strain-softening models run for the comparative studies and the peak stress obtained for each case are as given below:

Model 1: Independent extraction in III Seam to a height of 8.0m (two-pass): Peak stress = **9.24 MPa**
Model 2: Independent extraction in IV Seam to a height of 4.0m: Peak stress > **16 MPa**
Model 3: Simultaneous extraction in IV Seam to a height of 4.0m and III Seam to a height of 8.0m, with a stone and coal parting of 7m, pillar dimensions corresponding to 2.0 and 1.5 safety factors in IV and III seams, respectively (Table 5): Peak stress = **8.73 MPa**
Model 4: Simultaneous extraction in IV Seam to a height of 4.0m and III Seam in two sections to a height of 4.0m each, with a 5.0 m stone parting between IV and III(bottom) and 3.0m coal parting between III(bottom) and III(top), keeping vertically staggered configuration: Peak stress = **7.9 MPa**

The stress-strain curves and the plasticity states of Model 3 and Model 4 are given in Fig. 4(a) and 4(b), respectively. From the above study it has been concluded that vertically staggered configuration would lead to substantial reduction in the overall pillar strength, and hence not recommended for the extraction of III and IV Seams.

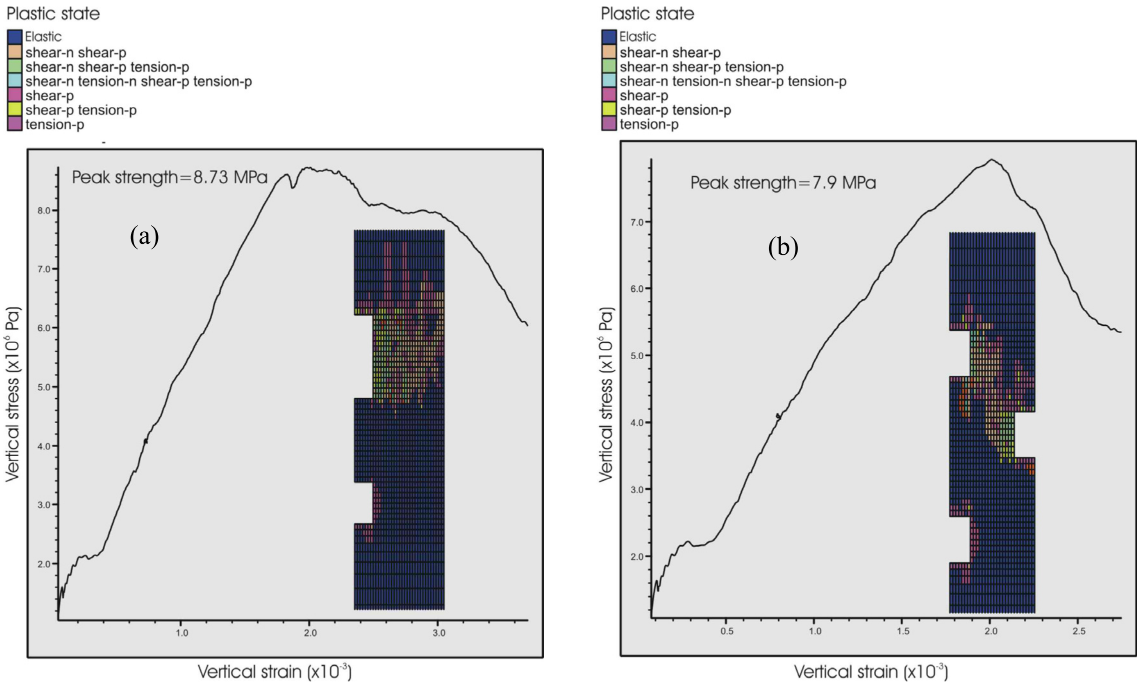

Fig. 4. Stress-strain curves and plasticity states for (a) Model 3 and (b) Model 4

11. Roof stability of web cuts

During high wall mining, the machine will go up to 350 m under unsupported span of 3.5m. Roof stability of these web cuts is assessed using elastic numerical modeling with local safety factor analysis (Loui et al., 2006). The models are constructed taking advantage of symmetry of the cutting pattern for all the seams. Vertical planes of symmetry have been taken, one passing through middle of the web pillar and the other passing through middle of the web cut. The models are constructed for all the seams, but for brevity the results are presented only for Seam III and IV.

In the first model, the III Seam extraction is taken along the roof and in second model it is taken 1.0m below the sandstone roof, leaving 1.0m coal. The depth and pillar dimension represents the long-hole region existing at the highest depth.

Block contours of safety factor obtained for the first model configuration are shown in Fig. 5(a). From the plot it is clear that at the centre of the roadway of III seam, safety factor are between 0.5 and 1.0 up to a height of 1m. On the other hand in IV seam, immediate roof shows the factor of safety more than 1.0. The second model results, as shown in Fig. 5(b), show considerable improvement in the roof safety factors, due to the 1.0m coal left against the weaker roof of III Seam. Though not presented here, stable roof scenarios are anticipated for Seams IIIA, II and I.

From the above elastic modeling studies it is recommended to leave 1.0m coal against the III Seam roof for better stability.

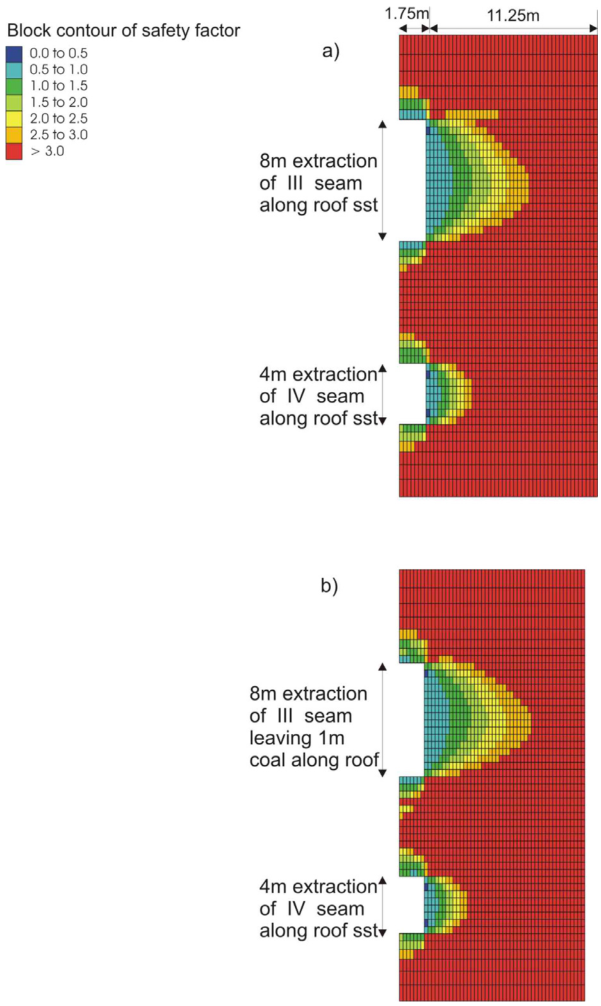

Fig. 5. Roof stability when III Seam extraction is (a) along the roof (b) leaving 1.0m coal along the roof

12. CONCLUSIONS AND Recommendations

From the empirical and numerical modeling design studies explained in this report, the following recommendations are made for safe extraction of all the five targeted seams at OCP-II by Highwall Mining.

1) The Highwall mining block is generally divided into Panel-A and Panel-B, the extraction cuts are planned in these panels along apparent dip and full dip directions, respectively.
2) Except in Seam-IIIA, all the seams are to be extracted in Panel-A and Panel-B. In Seam-IIIA, only Panel-B is proposed to be extracted.
3) Alternate long and short extraction cuts are designed in Seam IV, III and II.
4) An average extraction of 35% is achievable from all the seams.

13. Suggestions for future Highwall Mining operations

Highwall mining appears to have a great future in the Indian mining scenario, especially when demand for coal in the energy sector is rising quite steeply to sustain the fast track economic growth. It may be said that every open cast coal mine, theoretically, has a scope for highwall mining towards the end of its life, so why not plan in advance? In most of the Indian coalfields, multiple coal seams exist. Once the open pit reaches its limit and the final slope is formed, it will not be possible to make benches for working the upper seams. This will leave us with the option of extracting the seams by highwalling in ascending order, after leaving considerable amount of coal as support pillars for the top seams. Had these seams been wo ㅠ rked in a descending order the recovery could be significantly improved. As in the case of OCP-II, the extraction percentage is quite lower for the bottom seams due to the ascending sequence. To minimize such losses, a few suggestions are made.

1) When the open pit nears its boundaries and being worked with benches, the highwall operations may be planned in descending order. The working benches will provide platform for the extraction of the remaining portion of the seams.
2) The highwall operations may go parallel with the open-pit final slope formation in descending order.
3) A suitable backfilling technology may be developed in order to improve the recovery and ground condition, and to minimize the surface subsidence.
4) A suitable highwall cutter may be used such that it takes a narrow cut while entering and widens the cut while retreating by thinning down the web pillar on both the sides. This can give better ground conditions and can also improve the recovery.

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