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It is certified that the work contained in the thesis titled **NUMERICAL MODELLING STUDY OF THE EFFECT OF SOFTCOVER ON THE CAVING BEHAVIOUR OF STRATA AND SUPPORT REQUIREMENT IN DEPILLARING WORKINGS** by **SANDEEP KUMAR SAHOO** has been carried out under our supervision and this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

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Signature of Student

Date: 13.12.2021

Place: Varanasi

SANDEEP KUMAR SAHOO

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ABSTRACT

The review of literature, as well as the field experience, suggest that open-pit mining of deeper coal seams below the internal dumps of upper seam workings is exceptionally challenging. It is mainly due to the requirement of large scale rehandling of dump material, scarcity of land and unfavourable stripping ratio as observed in several open-pit workings in India. Practising underground mines are already there, but the engineering design based on a scientific knowledge base is unavailable. The overall condition results in poor ground control, uneconomical mining operation and foreclosure of mines. The mechanised Bord and Pillar mining with straight-line extraction of pillars is mainly preferred to facilitate mechanised extraction of developed pillars. Assessment of the strata mechanics and its associated ground control challenges are the primary concern for a safer depillaring operation. The placement of an overburden dump over the hardcover creates dead loading on the parting, reducing the overall stiffness of the composite overburden. The prevailing understanding of strata mechanics in depillaring working under the intact overburden requires fortification to design safer underground workings under softcover.

In cognisance of the contemporary situation, this dissertation aims to develop an approach to (a) study the influence of softcover on the caving behaviour of strata in a depillaring working, and (b) develop an approach for delineation of the safe thickness of the parting strata, and assessment of the goaf edge support requirement for a safer depillaring in such geo-mining conditions.

The significant contribution of this work include:

(a) field representative simulation of the caving behaviour of strata, compaction of periodically filled caved goaf and failure mechanism of the parting strata during progressive depillaring under softcover in a given geo-mining condition
(b) Procedure for obtaining characteristics curve of peak goaf edge convergence and criteria for deciding the safe thickness of parting strata and optimal goaf edge support capacity
(c) Procedure for estimating the peak settlement rate and location of failure of the parting behind the goaf edge and its relation with the efficacy of roof control
(d) A suitable orientation of the goaf line for easier caving of strata and reduced abutment loading in the depillaring working

Field Observation

The depillaring workings in the Indian geo-mining conditions are mostly overlain by intact overburden. The findings of the strata behaviour observations in such workings show average front abutment stress of 1.22 - 6.45 times with an average of 3.8 times the virgin stress at the cover depth of 40 – 250 m with an average of 128 m. Many of these workings have faced the problem of caving difficulty in the presence of sandstone rock formation in excess of 80% of the overburden. The large overhang in the goaf caused considerable goaf control problems apart from the poor stability of rib pillars and air blast. The maximum goaf edge convergence observed in these workings varied from 15 – 68 mm.

Underground mining under softcover in the overburden is new for the Indian geo-mining conditions. A suitable method of pillar extraction using continuous miner (CM) and mobile goaf edge support (MGES) could enable extraction of pillars for improved recovery and safety in such workings. Although practising mines are already there, the engineering design based on a scientific knowledge base is unavailable. The overall condition has resulted in poor ground control, uneconomical mining operation and foreclosure of mines. The studies conducted elsewhere show that softcover in the overburden significantly influences the severity of loading and deformation of the roof in depillaring workings. The support pillars are exposed to an increased load in the presence of the softcover. Excessive stress concentration before the roof collapse at the goaf edge has also been observed in such conditions. Although the span of main fall and periodic caving decrease with reduction in the thickness of the hardcover, the settlement of goaf in the presence of thin hardcover and thick softcover can be severe and uncontrolled with the formation of the abutment zone quite near to the working face. The compaction of goaf and resultant subsidence on the surface is also higher in the presence of softcover. The interval of periodic fracture increased while the abutment stress at the working face decreased with the increasing thickness of the parting strata.

Development of Numerical Modelling Approach for Simulation of Strata Behaviour and Goaf Edge Support Performance

A standard approach was developed for numerical simulation of strata and behaviour of goaf edge support in Bord and Pillar depillaring working under mixed overburden comprising of softcover and hardcover following the straight line of extraction. The Finite-Difference Code – FLAC 2D Version 7.0 (Itasca 2011) was used for this purpose. The model formulation consisted of the construction of model geometry, defining constitutive relation and material properties for rock mass and parting planes, *in situ* stress initialisation and assignment of boundary conditions of the model. The model geometry of a depillaring panel consists of floor strata overlain by a coal seam, immediate roof, and main roof, which form the caving zone in the overlying strata. The parting strata lie above the main roof. The combined thickness of the immediate roof, main roof and the parting strata forms the hardcover. The overburden dump material, termed as a softcover in this work, lies on the top of the hardcover. The physio-mechanical properties of the rock obtained from the laboratory tests are scaled-down, considering the scale effect and RQD of the strata to obtain the rock mass properties for utilisation in the numerical model. The Mohr-Coulomb plasticity model with tension cut off was used to simulate the roof failure under tension and shear. The strain-softening behaviour of the strata was also implemented to reduce the residual cohesive strength of strata either failed in tension or shear. The cohesive strength of strata that failed in shear was reduced to 10% of the peak strength while it was set to zero for strata that failed in tensile. The parting strata were modelled considering the Ubiquitous Joint model to allow growth of multiple sub-vertical fractures as it undergoes bending due to the transfer of the dead load from the softcover, lowering the overall stiffness of the overburden. Interface elements were used with pre-defined normal and shear stiffness and shear and tensile strength properties between the immediate roof and the main roof and the parting strata of the overburden to simulate the separation and differential bending of roof layers. In the absence of field-measured values, the theoretically estimated in situ stress field was initialised in the model. All modelling work has been done in large strain mode to simulate strata behaviour with progressive mining. The advance galleries were supported by hydraulic props of 40 t yield load capacity at an equal interval of 1 m to avoid modelling inconvenience arising due to the instability of the roof in the open galleries. The simulation of mobile goaf edge support considered in this study is similar to the powered roof support considered in Singh and Singh (2009a, 2010). The FISH sub-routine for simulating the failure of strata and their caving during the progressive depillaring of pillars was also similar.

A significant contribution of this work was the simulation of cyclic filling of the caved goaf during the periods of major caving by the addition of FISH sub-routines 'goaf_fill_design_mainfall' and 'goaf_fill_design_periodicfall' and integrating it with the above-mentioned FISH sub-routines. It comprised mapping the goaf filling zone, filling the mapped zone with strain hardening material, reallocation of the badly deformed grids and simulating the stress recovery and the modulus update of the goaf material as it received compaction due to the transfer of load through the parting strata with progressive mining. The material properties of the caved goaf were derived from the compressive strength and the bulking factor of the caved goaf material.

Parametric Numerical Modelling Study

A numerical modelling based parametric study was conducted to assess the effect of softcover on the strata and support behaviour in depillaring working. It considered the primary data by averaging the values compiled from different coalfields in India. The results of the study showed that the span of main fall varied from 36 to 42 m for change in PS/SC from 0.12 – 2.36 at the cover depth of 150 m. Similarly, the span of the main fall increased from 34 – 38 m for the PS/SC of 0.21 – 2.62 at 250 m and 31 – 36 m for the PS/SC of 0.24 – 1.79 at 350 m cover depth. For a given cover depth, the span of the main fall followed a non-linear increasing trend with increasing PS/SC, but it reduced with the increase in the cover depth (Figure 4.23). The previous work reported by Kushwaha and Banerjee (2005) and Wang et al. (2019c) supported these findings. The front abutment stress decreases with the increase in thickness of the parting strata. High parting thickness helps in controlled load transfer of the softcover, thereby preventing catastrophic settlement of the overburden. Similar results were also reported by Zhu et al. (2016) and Yang and Xia (2013, 2018).

The influence of PS/SC ratios on the front abutment stress ratio was evaluated in terms of the maximum and the average front abutment stress ratio at the cover depth of 150 – 350 m. The findings showed that the maximum and the average values of the FASR reduced with an increase in PS/SC at the shallow depth of cover. However, the maximum FASR remained almost the same at higher depth while the average FASR reduced with an increase in the PS/SC. The outcome of the work reported by Wang et al. (2019a) supported these findings. Although the overall loading pattern of the goaf edge support of 2 × 400 t capacity indicated marginally increased loading while working with lower PS/SC ratio at different cover depths, the study of the maximum and the average induced load could not establish any such relation indicating almost similar loading of the support in all the conditions.

The plot of the MGECS for different PS/SC ratios at the cover depth of 150 m showed a higher value of the maximum convergence for a lower value of the PS/SC. The maximum goaf edge convergence followed a non-linear reducing trend with an increase in the ratio of PS/SC. The range of MGECS at the cover depth of 150 m is 120 – 49 mm/m for PS/SC varying from 0.12 – 2.36. For cover depth of 250 m, the MGECS reduces from 102 – 55 mm/m for PS/SC of 0.21-2.62. The convergence reduced from 91 – 54 mm/m for PS/SC of 0.24 – 1.79 at 350 m cover depth. The comparative study at different cover depths revealed that the MGECS has a reducing trend with the increasing cover depth.

Behaviour of the Parting Strata

The behaviour of parting strata at the cover depth of 150 m showed almost sub-vertical tensile fractures in the parting strata during the settlement of the caved goaf with the progressive mining for PS/SC of 0.12 – 0.26. Such a trend indicated that the parting thickness was inadequate to develop any arching effect for a controlled load transfer of the softcover to offset its load towards the central region of the goaf pile. With a further increase in the PS/SC to 0.68, the orientation of tensile fracture planes indicated a noticeable bending with a reduction in the fracture density. The bending behaviour of parting strata for PS/SC ratio of 0.21 to 0.36 at the cover depth of 250 m indicated that the arching action of the parting strata was insufficient for a controlled load transfer. The parting strata with PS/SC of 0.81 exhibited appreciable bending as indicated by the orientation of the tensile fracture planes significantly tilted towards the goaf, along with a reduction in the fracture density. Similarly, for the cover depth of 350 m, the PS/SC ratio of 0.24 – 0.4 did not show any significant improvement in the bending behaviour of the parting. However, with a further increase in the PS/SC ratio to 0.86, the orientation of tensile fracture planes noticeably changed along with a reduction in the fracture density.

The maximum vertical settlement of the PS reduces with an increase in the PS/SC at a given cover depth. A sudden increase in the settlement is recorded at the failure of the PS under the dead load of the SC. At the cover depth of 150 m, the peak settlement of 1.34 m was observed for PS/SC of 0.12, which reduced to 0.28 m for the PS/SC of 2.36. The failure of the PS initiated at 44 m and completed on 46 m of the face advance for the PS/SC of 0.12. For the PS/SC of 2.36, the failure was initiated at 51 m and completed at 58 m.

Similarly, at the cover depth of 250 m, the peak settlement of 0.978 m was observed for PS/SC of 0.21, which reduced to 0.18 m for the PS/SC of 2.62. For PS/SC of 0.21, the failure of the PS initiated at 47 m and completed at 50 m of face advance. For the highest PS/SC of 2.62, the failure initiated at 62 m and completed at 64 m. At 350 m cover depth, the peak settlement of 0.642 m was observed for PS/SC of 0.24, which reduced to 0.221 m for the PS/SC of 1.79. For PS/SC of 0.24, the failure of the PS initiated at 39 m and completed on face advance of 49 m. For the highest PS/SC of 1.79, the failure initiated at 83 m and ended at 107 m. Due to its comparatively earlier rupture, thinner parting strata settle faster under a dead load of thicker softcover for a given cover depth. Such failure of the parting causes faster compaction and a reduced cover pressure distance of the goaf material. This observation agrees with the mechanisms of the parting failure explained by Zhou et al. (2015).

Stress Recovery in Caved Goaf

The vertical stress recovery in the goaf just after the main fall was 48% of in situ vertical stress for minimum PS/SC of 0.12 at the cover depth of 150 m. The peak stress was reduced to 20.5% for the maximum PS/SC of 2.36. The overall trend of stress recovery in the periodically filled goaf piles confirmed relatively higher stress for the lowest PS/SC. The minimum cover pressure distance of 39 m was obtained for PS/SC of 0.12, while the maximum length of 48 m was observed for PS/SC of 1.52. The goaf could not attain the cover pressure for PS/SC of 2.36. For PS/SC ratio of 0.12 – 1.52, stress recovered in the goaf to its virgin level at cover pressure distance of 0.26 – 0.32 times the depth of 150 m.

As the cover depth increased to 250 m, the stress recovered after the main fall was 36% of in situ vertical stress for minimum PS/SC of 0.21. The peak stress was reduced to 14% of the vertical stress for the maximum PS/SC of 2.62. The minimum cover pressure distance of 42 m is obtained for PS/SC of 0.21, while the maximum length of 103 m was observed for PS/SC of 2.62 in this condition**.** For PS/SC ratio from 0.21 – 2.62, the virgin stress recovered at a cover pressure distance of 0.17 – 0.41 times the cover depth.

At 350 m cover depth, the goaf could only develop vertical stress of 9.36% for the minimum PS/SC of 0.24. However, it increased to 15.8% for the maximum PS/SC of 1.79. The overall trend of stress recovered in the periodically filled goaf piles re-confirmed relatively higher stress for the lowest PS/SC. The minimum cover pressure distance of 89 m was obtained for PS/SC of 0.24, while the maximum length of 145 m was observed for PS/SC of 0.86. The goaf did not achieve cover pressure in the case of PS/SC of 1.79. The virgin stress recovered at a cover pressure distance of 0.25 to 0.42 times the cover depth in the PS/SC ratio from 0.24 – 0.86. However, it did not achieve cover pressure in the case of PS/SC of 1.79.

Design Criteria for Safe Parting Thickness and Optimal Support Capacity

A safe thickness of the parting strata between the caved zone and the softcover is essential for a controlled load transfer of the overburden and safer performance of the goaf edge support during progressive mining. The minimum thickness of parting strata (PS) for the safer load transfer of a given thickness of the softcover was decided considering an acceptable value of the maximum goaf edge convergence slope (MGECS). The plot of the MGECS as a function of the PS/SC showed that the maximum convergence at the goaf edge is strongly related to the ratio of the PS/SC for a given geo-mining condition. With increased PS/SC, the convergence reduced following a hyperbolic trend and finally became almost constant after a particular PS/SC. The characteristic curve of maximum goaf edge convergence slope for cover depth of 150-350 m in the parametric study was obtained as given by Equation 1.

$$\mathrm{MGECS} = 64.586\ (\mathrm{PS/SC})^{-0.269} \qquad \ldots[1]$$

The minimum thickness of the PS was determined by considering 75 mm/m of the maximum allowable convergence for containing the deterioration of the roof during the peak loading cycles of progressive mining within an acceptable limit. The PS/SC ratio of 0.57 was considered the design criteria for deciding the safe parting thickness for the given condition. The characteristic curves of the peak settlement rate (PSR) also confirmed the design limit of MGECS and the corresponding PS/SC for the controlled-load transfer.

The cut-off PSR at a cover depth of 150 – 350 m could be determined based on the safe PS/SC of 0.57 using Equation 2a-c. It represented the point where the settlement of softcover could be regulated in a safely controlled manner. The PSR remained held beyond this limit, as depicted by an almost flat trend line with a further increase in the PS/SC. It ensured that the parting strata were capable enough to prevent its uncontrolled movement under the influence of the dead load of the softcover, thereby preventing adverse convergence at the goaf edge. The safe PSR (peak settlement rate) at the cover depth of 150, 250 and 350 m was obtained as 100, 97 and 20 mm/m of face advance, respectively.

$$\mathrm{PSR}_{150} = 53.51(\mathrm{PS/SC})^{-1.131} \quad \ldots[2a]$$

$$\mathrm{PSR}_{250} = 57.048(\mathrm{PS/SC})^{-0.964} \quad \ldots[2b]$$

$$\mathrm{PSR}_{350} = 10.667(\mathrm{PS/SC})^{-1.119} \quad \ldots[2c]$$

The validity of the design limit of the MGECS was also verified by quantifying the location of failure of the parting strata behind the goaf edge. The results showed that the collapse of the PS takes place nearer to the goaf edge for lower PS/SC, thus transferring a higher load on support and convergence at the goaf edge. With the increase in the PS/SC ratio, the location of the failure relatively occurred away from the goaf edge, thus lowering the severity of load transfer in the depillaring working. The failure location in the parting strata increased following a non-linear trend with the PS/SC ratio increase. For the PS/SC at 0.57, the failure in the PS was indicated at 30 m behind the goaf edge.

Field Validation

The numerical modelling based approach as described above was validated through the case study of Kuiya Colliery in the Jharia Coalfield. The opencast working extracted the upper coal seam of the mine while the lower coal seam was standing on developed pillars. The open-pit mine had been backfilled with an OB dump of 44 m height. Later, it was proposed to reinitiate underground mining to work the lower coal seam located 49 m below the open-pit working. The average cover depth of the experimental panel was 93 m, which comprised 44 m of the softcover, 27 m of parting strata and 22 m of main and immediate roofs. The 4.9 m thick seam was developed along the floor for an extraction height of 3 m in a panel of 180 m ×120 m. The parting strata were comprised of two layers, 9 m thick loading roof and 18 m thick overburden. The average width of the developed pillar was 21 m × 21 m, while the gallery width was 4 m. The rock mass compressive strength of the roof strata varied from 7.61 – 15.62 MPa, while their tensile strength varied from 0.92 – 1.67 MPa. The ratio of PS/SC of the working was 0.61.

The effect of softcover on the caving behaviour of the strata and safe thickness of parting was evaluated by conducting numerical modelling based parametric study to quantify the MGECS for different PS/SC ratios. The peak settlement rate and the location of failure in the parting strata were also evaluated to cross-check the thickness of the safe parting for the site-specific condition. With the increase in the PS/SC ratio from 0.15 – 0.78, the span of the main fall showed only a marginal increase from 38 m to 40 m while working at the shallow depth of cover under softcover. The peak front abutment stress ratio (PFASR) showed a marginally decreasing trend, reducing from 4.16 to 4.06 for the PS/SC ratio increase from 0.15 – 0.78.

The parting strata developed numerous fractures in the goaf region for PS/SC of 0.15 – 0.42. Although the density of the fractures reduced with a further increase in the parting thickness, they merged over the central portion of the goaf. The uniformly spread failure of the parting strata indicated that the stiffness of the layer was inadequate to develop an appropriate arching effect under the load of the softcover. However, with the increase in the PS/SC ratio to 0.61, the tensile fracture planes that developed along the edge of 9 m thick lower parting strata overlain by the 18 m thick upper strata became sparse and slanted towards the goaf as the 44 m thick softcover settled on the surface. At the highest PS/SC ratio of 0.78, the fractures in the parting strata propagated following a uniform pattern, quite similar to the ratio of 0.61. However, the bending of the parting strata was further controlled, as reflected in improved stability at the goaf edge.

The vertical stress recovery in the goaf after main fall for different PS/SC ratios varied in the range of 0.98 – 1.05 MPa, which is 49 – 51% of the in situ vertical stress for the change in PS/SC from 0.15 – 0.78. The cover pressure distance for PS/SC of 0.15 was 21 m. As the PS/SC increased to 0.78, the cover pressure distance increased to 31 m. For the field representative condition where the PS/SC ratio is 0.61, the cover pressure distance was 28 m. The profile of vertical stress recovery in the goaf for the minimum and the maximum PS/SC indicated a marginally higher recovery of the vertical stress for the higher PS/SC.

The trend of the maximum goaf edge convergence slope (MGECS) as the function of the PS/SC ratio showed a decreasing trend of the MGECS in the range of 99-76 mm/m of face advance for PS/SC ratio varying from 0.15 – 0.78. The safe PS/SC ratio of 0.74 was estimated for prevailing field conditions.

The settlement for the 9 m thick loading layer was the maximum of 1.18 m for the minimum PS/SC of 0.15, which reduced to the minimum settlement of 0.67 m for the maximum PS/SC of 0.78. The overall settlement trend of the PS was in line with the findings of the parametric study. The peak settlement rate (PSR) of the parting strata decreased from 949 to 176 mm/m for the increase in the PS/SC from 0.15 – 0.78. The trend of the PSR confirmed that the settlement of the parting strata almost stabilised at PS/SC of 0.74. The threshold PSR of 166 mm/m was obtained for the safe PS/SC in the prevailing conditions.

The location of failure of the PS for the safe PS/SC ratio of 0.74 was 25 m behind the goaf edge. The result showed that the mine workings with 44 m thick softcover should have the parting strata with a minimum thickness of 32.6 m for a safe extraction at the cover depth of 93 m. This observation matched well with the permissible thickness of 29.37 m, as obtained by Xu et al. (2020) for the softcover of 48.4 m at the total cover depth of 97.77 m.

The parametric modelling study for support capacity varying from 2 × 200 t – 600 t was done to evaluate the support performance in the actual field conditions with a softcover of 44 m and a hardcover of 49 m. With the increase in capacity of the goaf edge support, the load on the support also increased during the progressive face advance. The support of 2 × 200 t experienced frequent yielding for a significantly increased period during the progressive depillaring. Although the yielding tendency of the support reduced with the increase in its load-bearing capacity, it induced a comparatively higher load during the progressive mining, confirming the findings of Barczak (1990). The goaf edge of the depillaring working received **c**onsiderably high convergence with the lowest support capacity of 2 × 200 t capacity. The maximum convergence reduced significantly with the increase in the support capacity. The optimal capacity for safer depillaring in the given condition was estimated as 2 × 437 t for containing the peak convergence within the safe limit.

The comparative study of the findings of the 2D model for the straight-line method of extraction and the 3D model for diagonal line extraction showed that the straight-line method of extraction provided a significantly favourable condition for easier caving of the strata and reduced abutment loading in the depillaring working. The caving of strata in the diagonal line is delayed considerably, and the front abutment stress is also higher in this case.

Based on the findings of the study, the following conclusions were drawn:

i. For a given cover depth, the span of the main fall follows a non-linear increasing trend with increasing PS/SC, but it reduces with the increase in the cover depth.

ii. The front abutment stress ratio is reduced with an increase in PS/SC ratio at a shallow depth of cover. However, the maximum FASR remains almost the same while the AFASR reduces at higher depth.

iii. The considerable thickness of parting strata helps in controlled load transfer of the softcover, thereby preventing catastrophic settlement of the overburden. The maximum and the average values of the FASR reduced with an increase in PS/SC at the shallow depth of cover. However, the maximum FASR remained almost the same at higher depth while the average FASR reduced with the PS/SC increase.

iv. The maximum vertical settlement of the parting strata showed a consistently reducing trend with the increasing PS/SC. A sudden and considerable surge in the ultimate settlement of parting strata indicated an uncontrolled load transfer.

v. As the parting becomes thicker and the SC becomes thinner with increasing PS/SC, the extent of failure in the parting reduces for a given cover depth of the working. Thicker parting undergoes only a partial rupture for the lower thickness of the softcover as indicated by a relatively minor or insignificant surge in the maximum displacement, meaning its controlled settlement with progressive face in such cases.

vi. The maximum goaf edge convergence followed a non-linear reducing trend with an increase in the ratio of PS/SC. The MGECS showed a reducing trend with the increasing cover depth as well.

vii. The orientation of the tensile fracture plane was a good indicator of the adequacy of the parting strata to develop any arching effect for a controlled load transfer of the softcover and offset its load towards the central region of the goaf pile. Inadequately thick parting showed almost sub-vertical tensile fractures. In contrast, the thicker parting showed fracture planes noticeably tilted towards the goaf area with a reduction in the fracture density, as noticed for PS/SC of 0.68 - 0.86 at the cover depth of 150 - 350 m. The tensile fractures that developed in the parting strata (PS) were almost sub-vertical for the lowest PS/SC ratio, indicating that the thickness of the PS was inadequate to create any arching effect for a controlled load transfer in the goaf edge region.

viii. Thinner parting strata settle faster under a dead load of thicker softcover at a given cover depth. Such failure of the parting causes higher compaction and a reduced cover pressure distance of the goaf material. However, the goaf does not attain the cover pressure even after a substantial goaf exposure for a very thick parting.

ix. The maximum convergence at the goaf edge is strongly related to the ratio of the PS/SC for a given geo-mining condition. The minimum thickness of parting strata (PS) for the safer load transfer of a given thickness of the softcover was decided for an acceptable maximum goaf edge convergence slope using the characteristic curve of maximum goaf edge convergence slope for different PS/SC. The minimum thickness of the PS can be determined by considering 75 mm/m of the maximum allowable convergence for containing the deterioration of the roof during the peak loading cycles of progressive mining within an acceptable limit.

x. The PS/SC ratio of 0.57 satisfied the design criteria of the safe parting thickness for the set of strata conditions in the parametric studies. Accordingly, the minimum parting thickness of 46 to 119 m was required for safer working in the presence of a limiting softcover thickness of 80-207 m at the cover depth of 150 – 350 m.

xi. The characteristic curves of the peak settlement rate (PSR) also confirmed the design limit of goaf edge convergence slope and the corresponding PS/SC for the controlled-load transfer. The failure in the parting strata was indicated 30 m behind the goaf edge in this condition.

xii. The estimated value of the safe PS/SC ratio was 0.74 for the Kuiya Colliery at the cover depth of 93 m. The mine workings with 44 m thick softcover required a minimum of 32.6 m thick parting strata for the safe extraction of pillars. The threshold PSR was 166 mm/m for the safe PS/SC in the prevailing conditions. The actual thickness of the parting was 17% smaller wrt the minimum required for safer transfer of the dead load of the softcover.

xiii. The optimal capacity for containing the maximum goaf edge convergence within the safe limit at Kuiya Mine was 2 × 437 t.

xiv. As the actual parting was marginally thinner, it was expected to produce a slightly higher convergence of 80 mm/m at the goaf edge. The location of failure of the PS for the safe PS/SC ratio of 0.74 was 25 m behind the goaf edge, while the actual parting was estimated to fail 23.5 m behind the goaf edge.

xv. Mechanised extraction following straight-line extraction method in conjunction with continuous miner and mobile goaf edge support can be an appropriate method for faster extraction of developed pillars under softcover.

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LIST OF SYMBOLS

Symbols	Description
σ_{cm}	Rock Mass Compressive Strength
σ_{tm}	Rock Mass Tensile Strength
σ_c	Intact Rock Compressive Strength
σ_t	Intact Rock Tensile Strength
E_m	Rock Mass Modulus
E	Intact Rock Modulus
K	Bulk Modulus
G	Shear Modulus
E	Young's Modulus
ν	Poisson's Ratio
C_{cm}	Cohesive Strength of Rock Mass
ϕ	Friction Angle
f_s	Mohr-Coulomb Shear Yield Function
f_t	Tension Yield Function
σ_1	Major Principal Stress
σ_2	Minor Principal Stress
F_n	Normal Force
F_s	Shear Force
u_n	Normal Displacement
u_s	Shear Displacement
L	Effective Contact Length
σ_v	Vertical Stress
γ	Unit Weight of Rock
K	Ratio of Average Horizontal Stress to Vertical Stress
β	Thermal Expansion Coefficient of Rock
G'	Geothermic Gradient
H	Depth from the Surface
E	Young's Modulus of Rock
K_w	Bulk Modulus of the Water-Oil Mixture

b	Bulking Factor of the Goaf Material
h_c	Caving Height
h	Extraction Height
ε_m	Maximum Axial Strain
L_p	Span of Periodic Caving
S_{mf}	Main Fall Span
E_o	Initial Tangent Modulus
RQD	Rock Quality Designation

ABBREVIATION

AFASR	Average Front Abutment Stress Ratio
BCCL	Bharat Coking Coal Limited
CD	Cover Depth
CCL	Central Coalfields Limited
CM	Continuous Miner
DGMS	Directorate General of Mines Safety
ECL	Central Coalfields Limited
FASR	Front Abutment Stress Ratio
GRC	Ground Response Curve
GMSUR	Goaf Modulus and Stress Update Routine
GECS	Goaf Edge Convergence Slope
GSI	Geological Strength Index
HC	Hardcover
MBLS	Mobile Breaker Line Support
MCL	Mahanadi Coalfields Limited
MGES	Mobile Goaf Edge Support
MGECS	Mobile Goaf Edge Convergence Slope
MRS	Mobile Roof Support
OB	Overburden
PS	Parting Strata
PSR	Peak Settlement Rate
PFASR	Peak Front Abutment Stress Ratio
RMR	Rock Mass Rating
RQD	Rock Quality Designation
SAGES	Self-Advancing Goaf Edge Support
SC	Softcover
SCCL	Singareni Collieries Company Limited
SECL	South Eastern Coalfields Limited
WCL	Western Coalfields Limited