CHAPTER 7

DISCUSSION

7.1 General

Open-pit mining of lower coal seams below the internal dumps of upper seam working is extremely challenging due to the requirement of large scale rehandling of dump material, paucity of land and unfavourable stripping ratio as observed in a number of open-pit workings in India. A number of proposals have been floated for the extraction of such coal seams by an underground method of mining to avoid these constraints. The mechanised Bord and Pillar mining with straight-line extraction of pillars is mainly preferred to facilitate mechanised extraction of pillars at a faster pace. 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 for the design of safer underground workings under softcover.

7.2 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 (Wang et al. 2019a).

7.3 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 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 normal and shear stiffness of 10 MPa/m, further adjusted to avoid excessive penetration of nodes at higher depths of cover along with zero tensile bond, the cohesive strength of 1 kPa and friction angle of 15°, in between the immediate roof and the main 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 for a realistic simulation of 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.

7.4 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. A seam thickness of 3 m was considered for its complete extraction in all the cases. The height of the caving zone is 24 m, comprising of 6 m thick immediate roof and 18 m thick main roof, which is eight times the height of extraction. The thickness of the parting strata and the softcover has been varied in different proportions keeping the depth of working between 150 – 350 m, considering the most likely condition for the adoption of underground mining below softcover. The thickness of the parting strata was varied from 13.5 – 209.3 m, marking the total thickness of the hardcover from 37.5 – 233.3 m, while the thickness of the softcover varied from 37.5 – 262.5 m. The progressive mining was simulated in the plane strain condition to observe the failure and caving of strata till the cumulative advance of goaf edge just exceeded the maximum thickness of parting strata for a given depth of cover. The idea was to obtain the response of parting strata of different thicknesses as it undergoes failure under the loading of the softcover with progressive depillaring in a given geo-mining condition. In all the parametric models, a mobile goaf edge support of 2 × 400 t capacity was deployed at the goaf edge with specific setting-yield stiffness characteristics. The filling of caved goaf during the main fall and the periodic caving was also simulated in this process to study the compaction and stress recovery in the goaf and the behaviour of the parting strata during progressive mining. The model results considered basic parameters like the span of main fall, front abutment stress, load on the goaf edge support, goaf edge convergence, and compaction of the cyclically filled caved goaf material with progressive extraction of the developed pillars. The settlement rate of the parting strata was also evaluated upon its first failure during the simulated depillaring. All these parameters were assessed as a function of the ratio of the thickness of parting strata to the softcover thickness for cover depth varying from 150 – 350 m.

(a) Strata and Support Behaviour at Cover Depth of 150 m

The modelling results for 150 m cover depth showed that for the increase in thickness of parting strata (PS) from 13.5 to 88.5 m and reduction in softcover (SC) from 112.5 – 37.5 m (PS/SC ratio varying from 0.12 – 2.36), the main fall span received a marginal increase from 36 – 42 m. For the thinnest PS of 13.5 m overlain by 112.5 m thick SC (PS/SC = 0.12), the main fall initiated at 36 m of face advance, leaving some tensile failure zones in the overhang of the main roof. With increasing thickness of parting strata and reducing thickness of softcover, the extent of tension zones decreased, and the main roof caved after a slightly increased face advance. With the increasing ratio of PS/SC, the abutment stress ratio (peak abutment stress/vertical stress in the in situ condition) reduced. The load on the goaf edge support of 2 × 400 t capacity showed a marginally increased loading while working under the lowest PS/SC ratio. The goaf edge convergence slope also reduced from 120 to 49 mm/m, with the PS/SC ratio increasing from 0.12 to 2.36. The maximum convergence was observed while a rib of 1 – 2 m was left against the advance gallery owing to the poor stability of the rib pillar combined with the loading of the overhang undergoing failure over the goaf edge support.

The parametric study at the shallow depth of cover considered a few conditions wherein the thickness of the parting strata was 13.5 m and 26 m, compared to the caving zone of 24 m. In both of these cases, the parting strata ultimately failed with dense fracture signifying excessive bending of the parting and its inability to bridge the load of the softcover, causing excessive transfer of load near to the goaf edge. Such failure of the parting strata induced immense abutment stress and load on the goaf edge support near the working face, confirming the findings reported by Zhang et al. (2016). 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. With increasing thickness, the orientation of tensile fracture planes formed in the PS over the goaf pile indicated a noticeable bending and a reduction in the fracture density. It did not undergo complete rupture when the parting strata got very thick than the softcover.

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 maximum settlement for PS/SC of 0.12 – 0.26 indicated an uncontrolled load transfer. A combined study of the PS displacement trend and its failure profile with progressive face advance showed that as the parting becomes thicker and the SC becomes thinner with increasing PS/SC, the extent of failure in the parting reduces. 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.

The vertical stress recovery in the goaf for different PS/SC at 150 m depth shows that for minimum PS/SC of 0.12, the stress recovered in the goaf just after the main fall was 48% of in situ vertical stress. The peak stress after the main fall reduces to 20.5% of the peak stress for the maximum PS/SC of 2.36. The overall trend of stress recovered 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 distance of 48 m is observed for PS/SC of 1.52 while the goaf could not attain the cover pressure for PS/SC of 2.36 because of the bridging action of the extremely thick parting against thinner softcover.

(b) Strata and Support Behaviour at Cover Depth of 250 m

The modelling results of caving behaviour at the cover depth of 250 m for the thickness of parting strata (PS) varying from 38.5 to 163.5 m and softcover (SC), varying from 62.5 to 187.5 m (PS/SC ratio from 0.21 – 2.62), showed that for the thinnest PS of 38.5 m overlain by 187.5 m thick SC, the main fall span received only a marginal increase from 34 m for the lowest PS/SC of 0.21 to 38 m for PS/SC of 0.81 and then it remained constant. The plot of front abutment stress with face advance for different PS/SC ratios showed a similar trend as observed at 150 m cover depth**.** The abutment stress was higher with the minimum PS/SC ratio of 0.21 compared to that with the higher PS/SC ratio. However, the peak FASR was only marginally higher for the lowest PS/SC. The overall profile of load on the support showed a marginally increased loading while working under the lowest PS/SC ratio. It achieved the yield load at several stages during the progressive mining for the minimum as well as the maximum ratio. The maximum GECS reduced from 102 to 55 mm/m for the increase in PS/SC from 0.21 – 2.62. These maximum goaf edge convergence values were observed while crossing the advance gallery at 78 – 82 m location.

The damage pattern of parting strata for PS/SC of 0.21 showed the development of almost sub-vertical tensile fractures in the 38.5 m thick parting against the dead load of 187.5 m thick softcover during the settlement of the caved goaf with the progressive mining. Such failure profile of the parting indicated that its thickness was inadequate to develop any arching effect for a controlled load transfer of the softcover in the goaf edge region. With the increase in the PS/SC ratio to 0.36, a noticeable change in the orientation of the fracture planes was noted. However, these fractures subsequently merged, indicating that the arching action of the parting strata was still insufficient to offset the load of the softcover towards the central region of the goaf pile. With a further increase in the PS/SC to 0.81, the tensile fracture planes tilted towards the goaf as they grew from the bottom towards the top of the layer, along with a reduction in the fracture density. A similar trend continued with the PS/SC ratio of 1.71 and 2.62. The maximum vertical settlement of the parting strata for different PS/SC ratios followed a consistently reducing trend with the increase in PS/SC. However, the relative difference between the maximum displacement observed for PS/SC of 1.71 and 2.62 is very small. A sudden surge in the maximum settlement for PS/SC of 0.21 – 0.36 marked a sudden rupture of the parting due to its inadequateness to control the load of the thicker softcover. Such behaviour of the parting indicated an uncontrolled load transfer. As the parting became thicker and the SC became thinner with increasing PS/SC, the parting received only a partial rupture as indicated by a relatively smaller surge in the maximum displacement in such cases. When the thickness of the parting got significantly larger than the softcover, no noticeable surge in its displacement trend was recorded, indicating its controlled settlement with the progressive mining. The combined study of the displacement trend and the failure of parting strata showed a marked reduction in the extent of failure in the parting with increasing the PS/SC. The partial rupture of relatively thicker parting led to a smaller or insignificant surge in the maximum displacement, indicating its controlled settlement with the progressive face.

The vertical stress recovery in the goaf for PS/SC of 0.21 at 250 m depth showed a stress recovery of 36 % of the in situ vertical stress just after the main fall. The stress recovery after the main fall reduced to 14% of the virgin stress for the maximum PS/SC of 2.62. The overall trend of stress recovered in the periodically filled goaf piles re-confirmed relatively higher stress for the lowest PS/SC as observed in the shallow cover depth of 150 m. The minimum cover pressure distance of 42 m was obtained for PS/SC of 0.21, which increased to 103 m for PS/SC of 2.62.

(c) Strata and Support Behaviour at Cover Depth of 350 m

The span of the main fall varied from 31 – 36 m for the thickness of PS increasing from 63.5 – 151 m along with the simultaneous reduction in SC from 262.5 – 175 m (PS/SC ratio varying from 0.24 to 0.86) and remained constant after that. The abutment stress was relatively higher for the minimum PS/SC of 0.24 compared to that with PS/SC of 1.79. The overall profile of the support load shows higher loading while working under lesser PS/SC. The maximum GECS observed during progressive depillaring reduces with an increase in the PS/SC ratio. The maximum GECS of 91 mm/m was observed for the lowest PS/SC of 0.24, which reduced to 54 mm/m for the highest PS/SC of 1.79. These values of the maximum convergence were observed while crossing the advance gallery. The study of the bending behaviour of the parting strata and the recovery of goaf stress showed the development of sub-vertical tensile fractures developed in the parting strata during the settlement of the caved goaf for PS/SC of 0.24 when the thickness of the parting strata and the softcover was 63.5 m and 262.5 m respectively. The thickness of the parting strata was inadequate to develop any arching effect for a controlled load transfer of the softcover in the goaf edge region. With the increase in the PS/SC ratio to 0.4, a noticeable change in the orientation of the fracture planes was noted. However, the arching action of the parting strata was still insufficient to offset the load of the softcover towards the central region of the goaf pile. With a further increase in the PS/SC to 0.86, the orientation of tensile fracture planes noticeably slanted towards the goaf, along with a reduction in the fracture density. A similar trend continued with the PS/SC ratio of 1.79 as well.

The maximum vertical settlement of the parting strata was observed for the lowest PS/SC of 0.24, where the thickness of the parting strata is 63.5 m while the softcover is 262.5 m. The minimum cumulative settlement of the parting strata was noted for the highest PS/SC of 1.79, where the thickness of parting strata is 209.3 m while the softcover is 116.7 m. The cumulative settlement of the parting strata followed a consistently reducing trend with the increase in PS/SC. A sudden surge in the maximum settlement was recorded for PS/SC of 0.24 – 0.40, marking a complete rupture of the parting during progressive depillaring. The combined study of the displacement trend and the failure profile observed with progressive face advance showed a reduction in failure in parting strata with the increasing PS/SC. The partial rupture of relatively thicker parting leads to a smaller or insignificant surge in the maximum displacement, indicating its controlled settlement with the progressive face advance. The vertical stress recovery in the goaf for different PS/SC at 350 m depth showed that the stress recovered in the goaf just after the main fall was 9.36% of in situ vertical stress for minimum PS/SC of 0.24. The peak stress after the main fall increased to 15.8% of the in situ vertical stress for the maximum PS/SC of 1.79. The overall trend of stress recovered in the periodically filled goaf piles re-confirms relatively higher stress for the lowest PS/SC (Figure 4.22). 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.

7.4.1 Overall Strata Behaviour

The overall results of the parametric study showed that the span of the 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 (Table 4.12). 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 (Table 4.13) 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.

7.4.2 Failure 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 (Figure 4.20c).

7.4.3 Settlement of Parting Strata

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 49 m of face advance. 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).

7.4.4 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 (Figure 4.8). 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. Wang et al. (2017) reported 80% stress recovery at a similar cover pressure distance of 0.29 times the cover depth of 160 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 (Table 4.8). 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. In contrast, Zhang et al. (2017) observed 95% of stress recovery in the goaf, with a lesser cover pressure distance of 0.17 times the cover depth of 298 m in the intact strata condition.

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 1.79. At a similar depth of 390 m, Li et al. (2015) reported a stress recovery of 89% of the original stress at a distance of 0.23 times the depth.

7.5 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 5.1.

$$\mathrm{MGECS} = 64.586\ (\mathrm{PS/SC})^{-0.269} \qquad \ldots(5.1)$$

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 7.1a–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.

$$\mathrm{PSR}_{150} = 53.51(\mathrm{PS}/SC)^{-1.131} \qquad \ldots(7.1a)$$

$$\mathrm{PSR}_{250} = 57.048(\mathrm{PS}/SC)^{-0.964} \qquad \ldots(7.1b)$$

$$\mathrm{PSR}_{350} = 10.667(\mathrm{PS}/SC)^{-1.119} \qquad \ldots(7.1c)$$

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.

7.6 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 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. 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 significantly delayed, and the front abutment stress is also higher in this case.