CHAPTER 6

MODEL VALIDATION

This chapter deals with the validation of the numerical modelling approach to assess the influence of softcover on the caving behaviour of strata in a depillaring working, and delineate the safe thickness of the parting strata, and estimate the goaf edge support requirement for a safer depillaring in such geo-mining conditions. The validation work was performed with regard to the conditions prevailing at Kuiya Colliery in the Jharia Coalfield. Based on the understanding developed in the parametric study, the maximum goaf edge convergence was used to determine the safe parting thickness. 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. The optimum capacity of the goaf edge support for safe depillaring in the given geo-mining condition has also been estimated. A three-dimensional modelling study of the depillaring working has also been undertaken to compare the findings of depillaring following the diagonal line with the straight line extraction as represented by the plane strain model.

6.1 About the Mine

Kuiya Colliery is located in Jharia Coalfield in the state of Jharkhand, India (Figure 6.1). It is under the Bastacolla area (Area IX) of BCCL. In this mine, the upper coal seam was mined by opencast working while the lower coal seam was standing on developed pillars. The open-pit mine was 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.

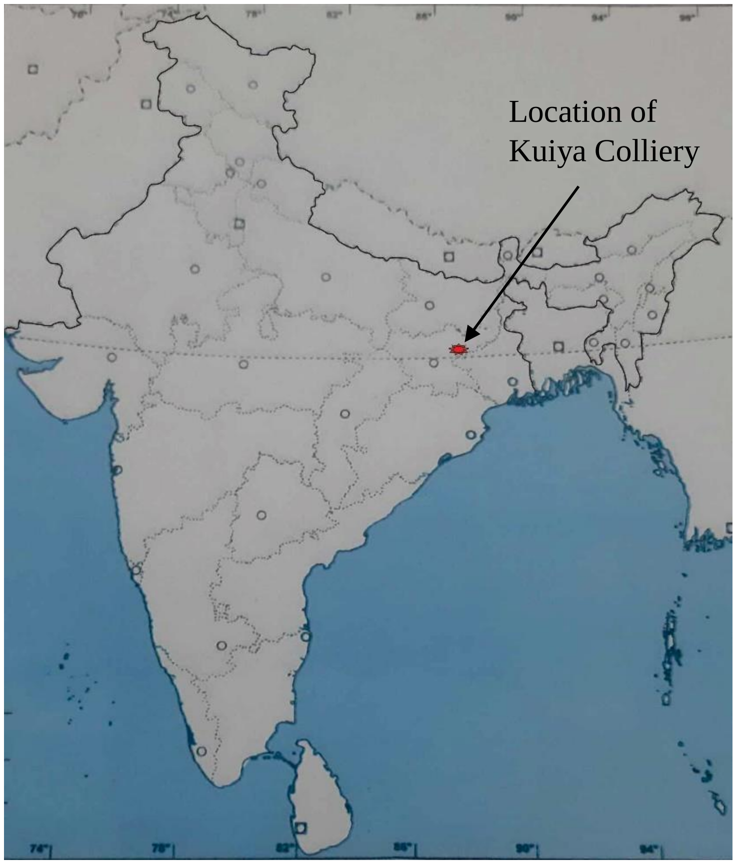


Fig. 6.1. Map of India showing the location of Kuiya Colliery

6.1.1 Depillaring Panel and Borehole Section

The depillaring panel under study was 180 m long and 120 m wide (Figure 6.2). The thickness of the coal seam was 4.9 m which was developed along the floor for 3.0 m height. The average depth of cover was 93 m which comprised of 44 m of the softcover, 27 m of parting strata and 22 m of main and immediate roofs combined together that formed the caving zone. The average size of the developed pillar was 21 m × 21 m, while the gallery width was 4 m.

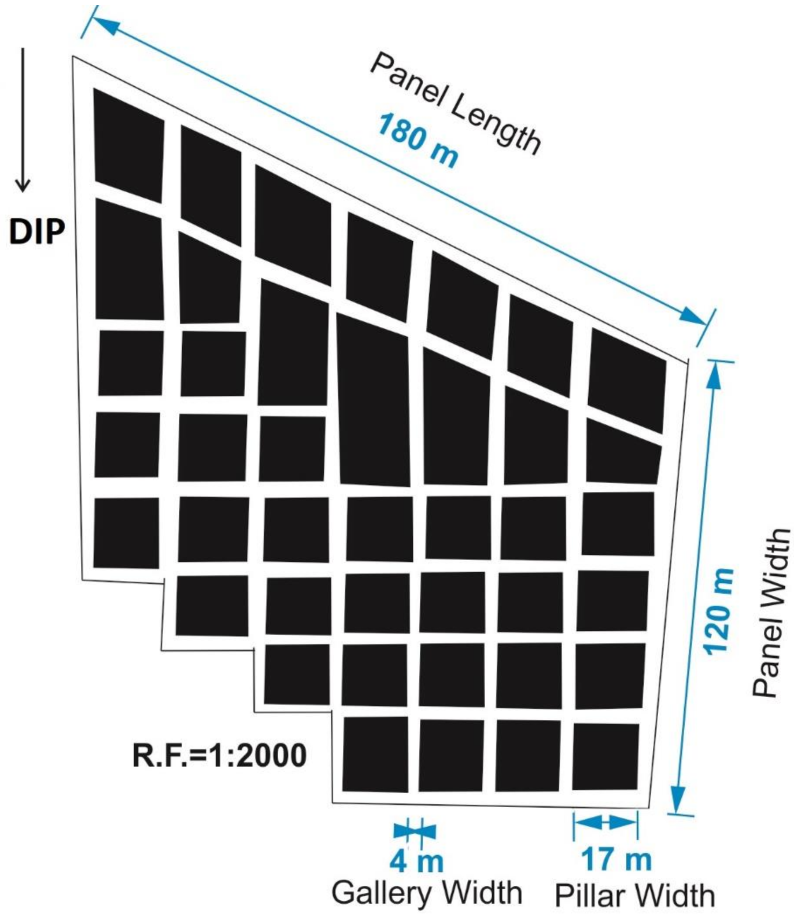


Fig. 6.2. Schematic Plan of the depillaring panel at Kuiya Colliery

The stratigraphy of the overlying strata (Figure 6.3) shows that the 7.36 m thick immediate roof was comprised of medium-grained sandstone and shale, while the 14.64 m thick main roof was formed of coarse to medium-grained sandstone with shale band, shaly sandstone, and, coarse-grained sandstone with coal band. The parting strata comprised of 9 m thick loading roof and 18 m thick upper strata. The softcover comprising of 44 m thick overburden dump had been placed on the top of the upper strata. Table 6.1 shows the field-representative rock mass properties of the strata of this working.

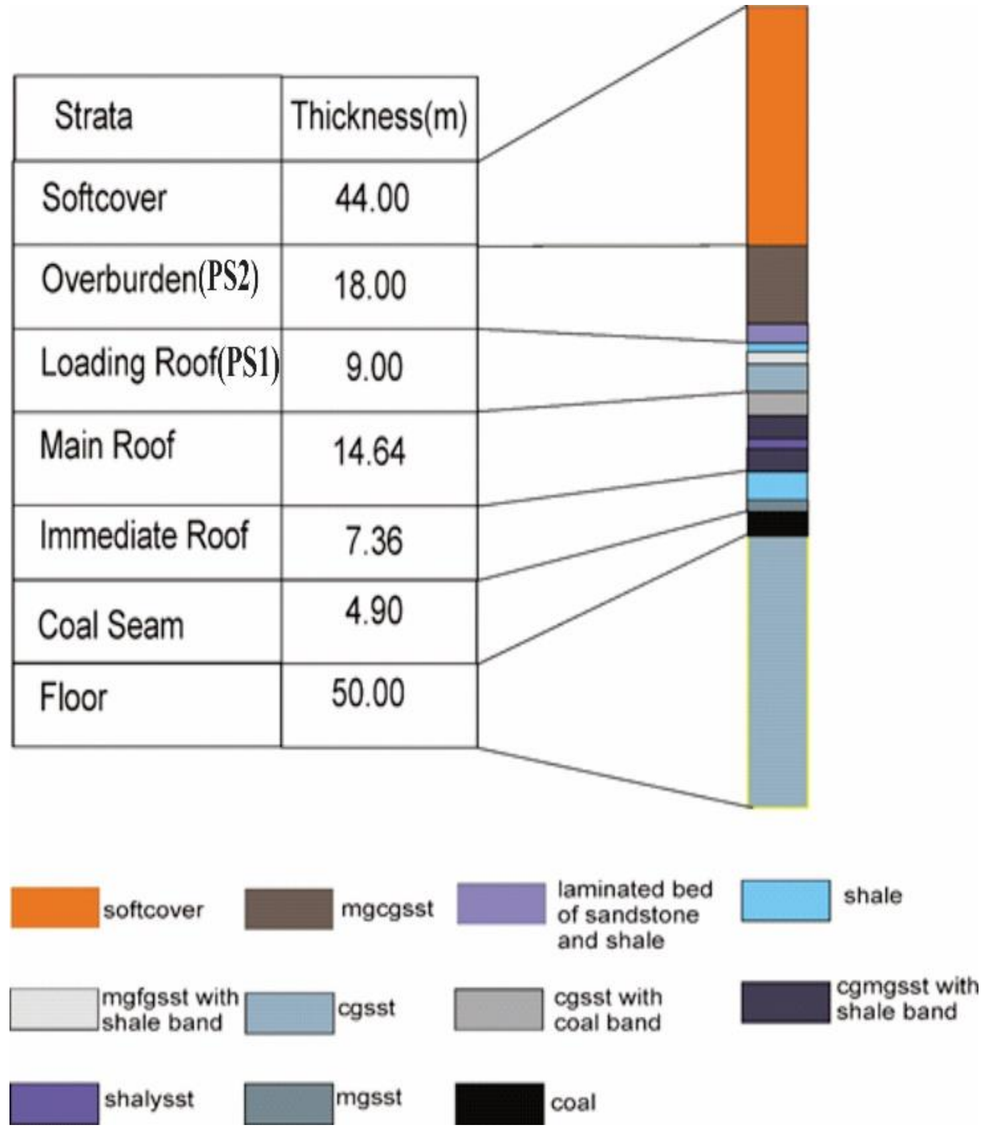


Fig. 6.3. Borehole Section of overlying strata at Kuiya Colliery

Table 6.1. Rock mass properties of Kuiya Colliery

Strata	Thickness, m	Density, kg/m^3	Young's Modulus, GPa	Tensile strength, MPa	Cohesion, MPa	Friction angle,°	Dilation angle,°
Softcover	44.00	2000	0.072	0	0.09	25	2
Overburden	18.00	2358	11.50	1.64	3.65	40	5
Loading roof	9.00	2387	11.20	1.67	3.28	40	5
Main roof	14.64	2333	9.88	1.49	3.17	40	5
Immediate roof	7.36	1936	8.05	0.92	1.78	40	5
Coal seam	4.90	1400	2.00	0.20	0.49	25	2
Floor	50.00	2387	11.20	1.67	3.28	40	5

6.2 Numerical Modelling

The numerical model of the depillaring working was formulated using the approach discussed in Chapter 3. The 27 m parting strata comprised of two strata units, 9 m thick loading roof and 18 m thick overburden. The parting strata was overlain by the 44 m thick softcover of overburden dump material. Zone size in the immediate roof varies from 0.54 to 1.16 m in the vertical direction. In the main roof, the zone size varied from 1.08 to 2.31 m. However, the zone size in the parting strata was uniformly maintained as 2.25 m. The parting strata was assigned constitutive property of the Ubiquitous Joint material, whereas the strata within the caving zone was modelled as the Mohr-Coulomb strain-softening material. The virgin and development models of the depillaring working are depicted in Figures 6.4a and 6.4b.

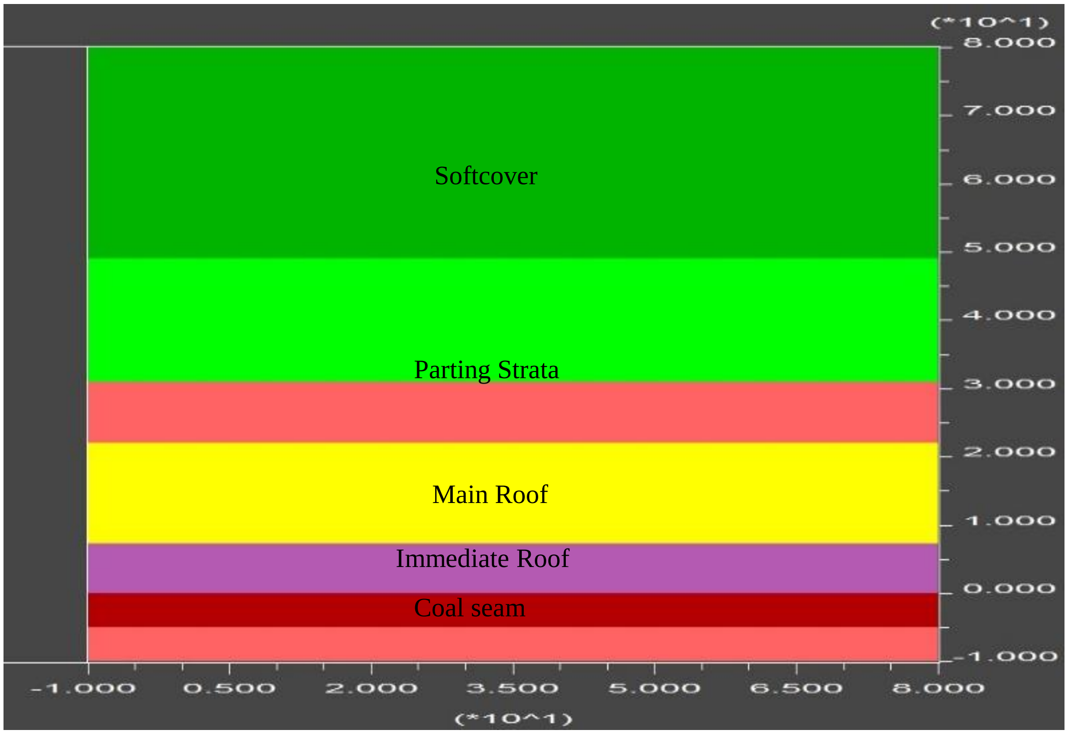


Fig. 6.4a. Virgin model of the depillaring working under softcover at Kuiya Colliery

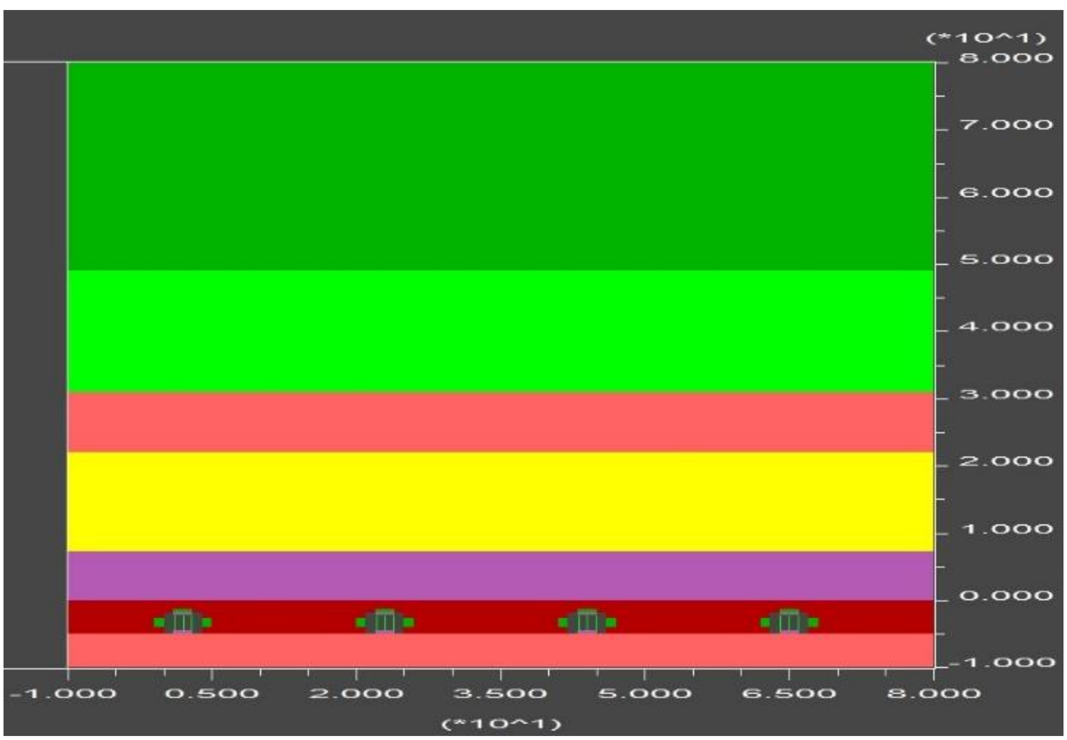
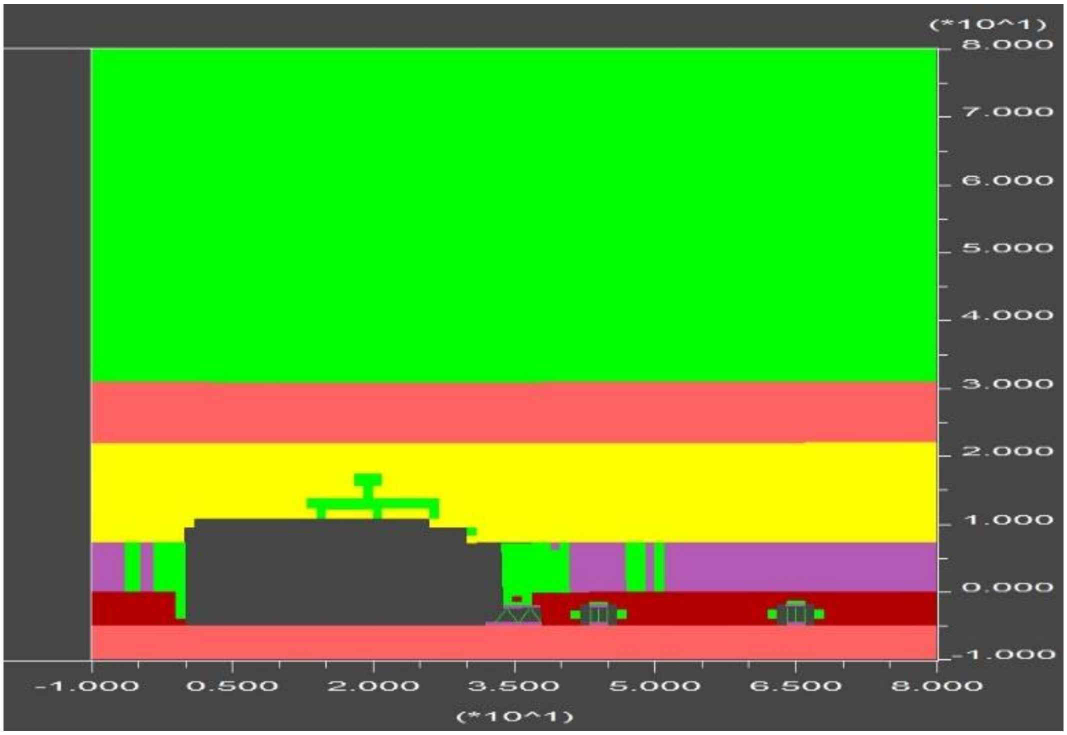


Fig. 6.4b. Developed headings in the plane strain condition

During development in the coal seam, galleries of 4 m × 3 m size were created along the floor, leaving solid pillars of 17 m in-between (Figure 6.4b) and a 1.9 m thick layer of coal in the roof. Three hydraulic props of 40 t yield load capacity were installed in each gallery at an equal interval of 1 m which was assigned with the diameter of 12 cm as in the field condition. The setting load of each prop was 10 t and the prescribed axial displacement to reach its designed yield load was 31 mm. The support density so applied in each gallery was 2.5 t/m^2 in the plane strain condition. The capacity of the goaf edge support was 2 × 400 t, which was set at 60% of the yield load in each mining cycle.

6.3 Effect of PS/SC on the Strata and Support Behaviour

In the actual mining condition prevailing at Kuiya Colliery, the 27 m thick parting strata comprise of two layers; the lower layer, which acts as the loading layer (Obert and Duvall, 1967), is 9 m thick while the upper layer is 18 m thick. The softcover of the OB dump is 44 m thick, creating PS/SC ratio of 0.61. The variation in thickness of the PS and SC was made by changing the thickness of the upper layer and adjusting the thickness of the softcover accordingly to maintain the same cover depth (Figure 6.5). Figure 6.6 shows the plot of the main fall span for the varying PS/SC ratio at the cover depth of 93 m. It shows that with the increase in the PS/SC ratio, the main fall span increases only marginally while working under softcover at the shallow cover depth (Table 6.2).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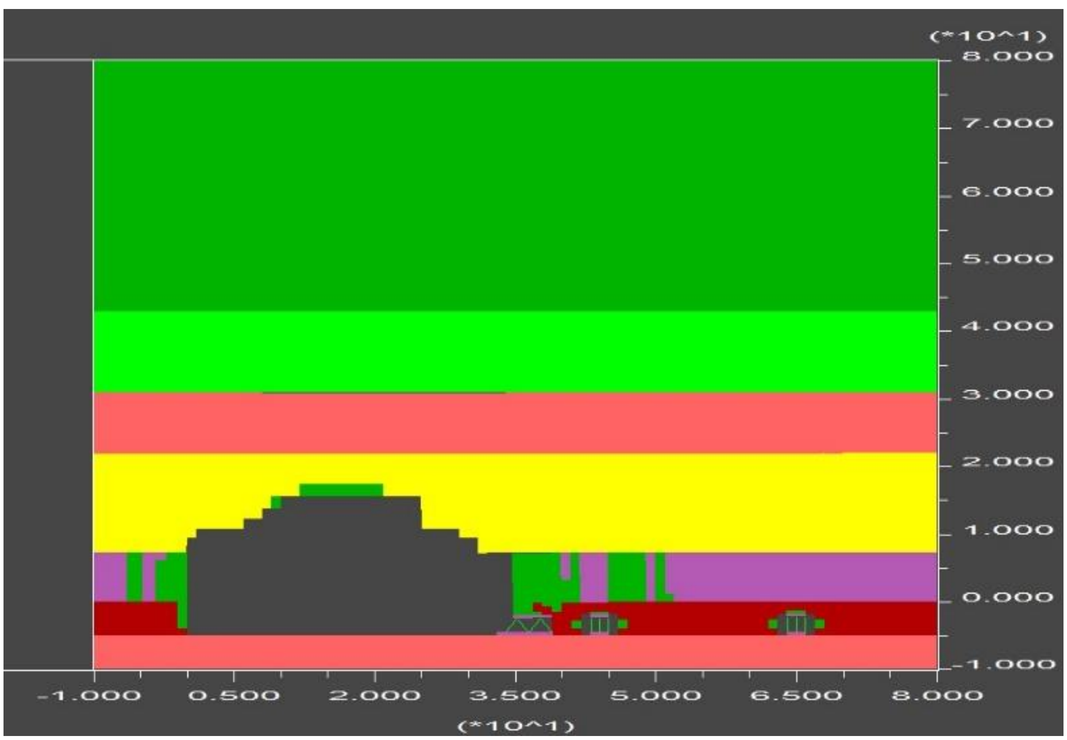
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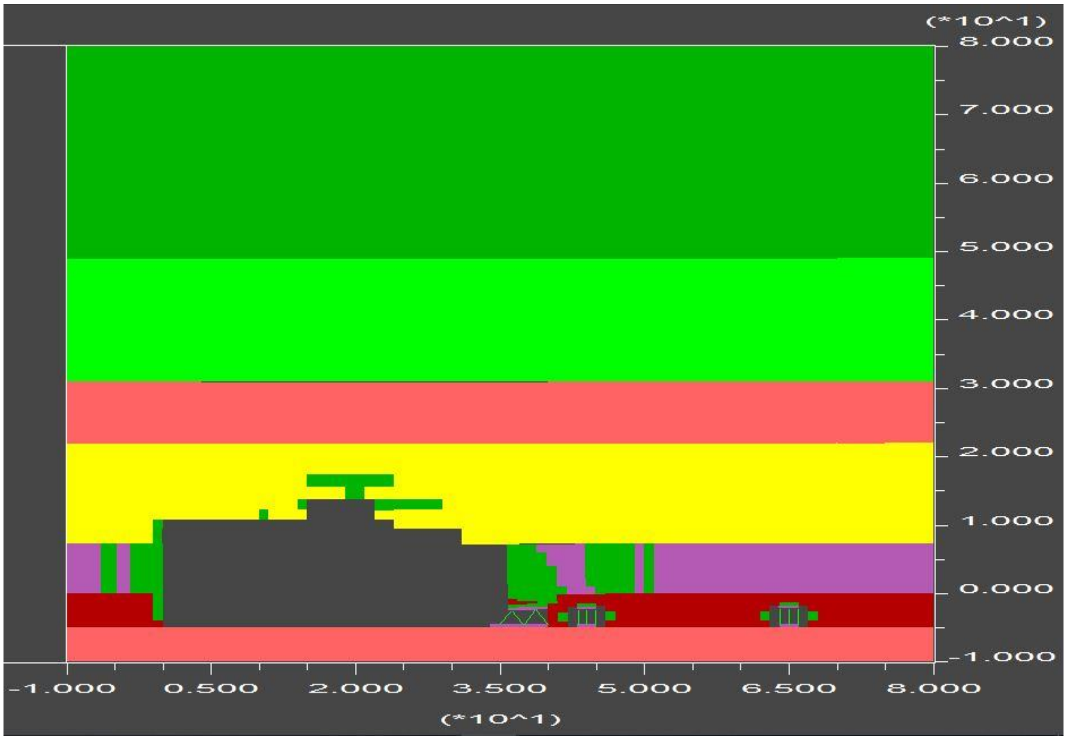

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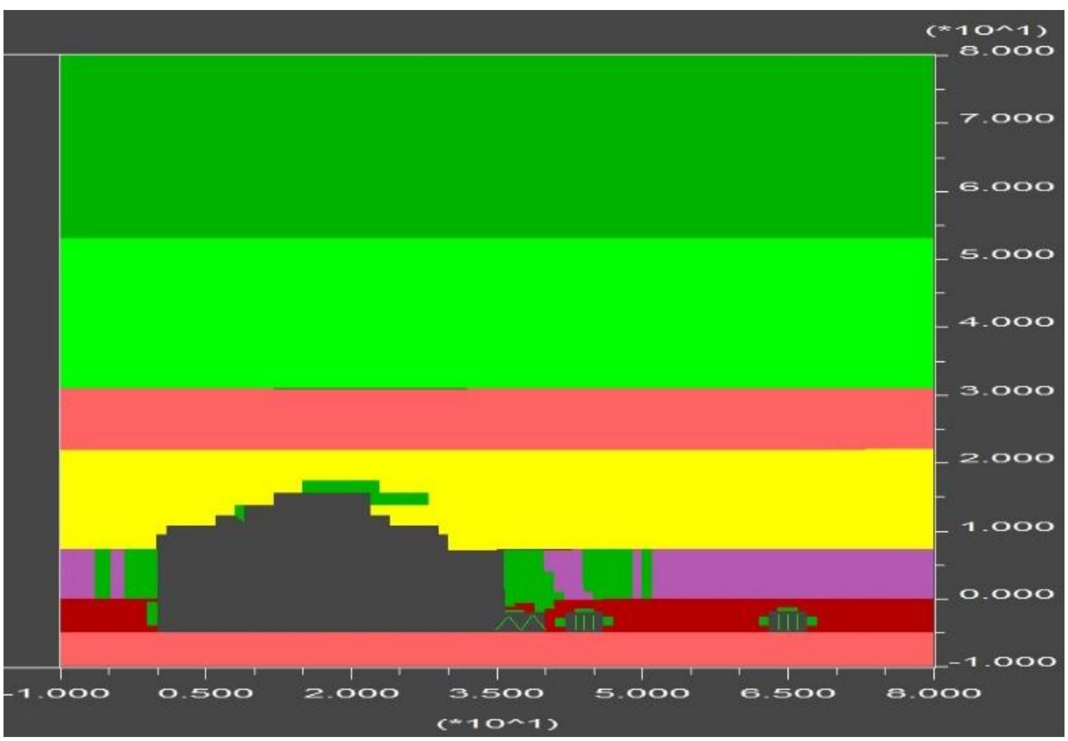

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Fig. 6.5. Occurrence of main fall for different PS/SC ; (a) 38 m face advance, PS/SC = 0.15, (b) 39 m face advance, PS/SC = 0.42, (c) 40 m face advance, PS/SC = 0.61, (d) 40 m face advance, PS/SC = 0.78

Table 6.2. Main fall span for varying PS/SC at Kuiya Colliery

SC, m	PS, m	HC, m	HC/SC	PS/SC	Main fall span, m
62	9	32.90	0.53	0.15	38
50	21	44.90	0.90	0.42	39
44	27	50.90	1.16	0.61	40
40	31	54.90	1.37	0.78	40

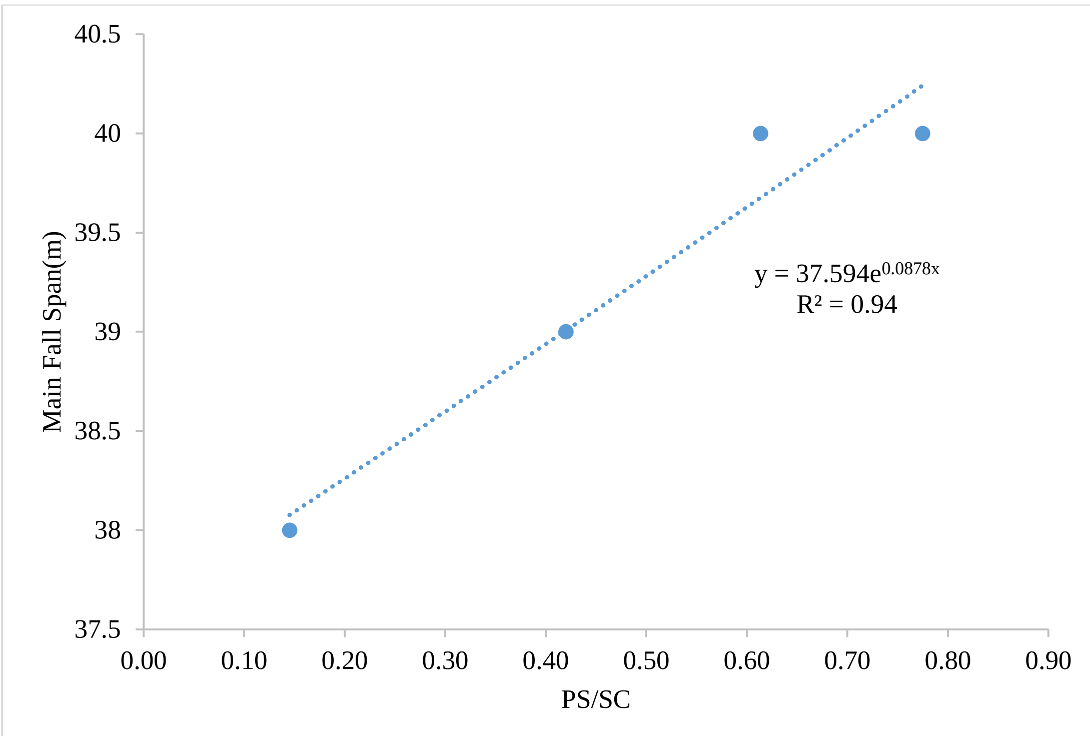


Fig. 6.6. Main fall Span for various PS/SC at Kuiya Colliery

The study of the front abutment stress ratio (FASR) for changing PS/SC values showed a marginal reduction in the peak FASR (PFASR) from 4.16 to 4.06 for the increase in the PS/SC ratio from 0.15 – 0.78. The PFASR follows a decreasing trend with the PS/SC ratio (Figure 6.7). It is similar to the findings obtained in the parametric study for the shallow cover depth of 150 m.

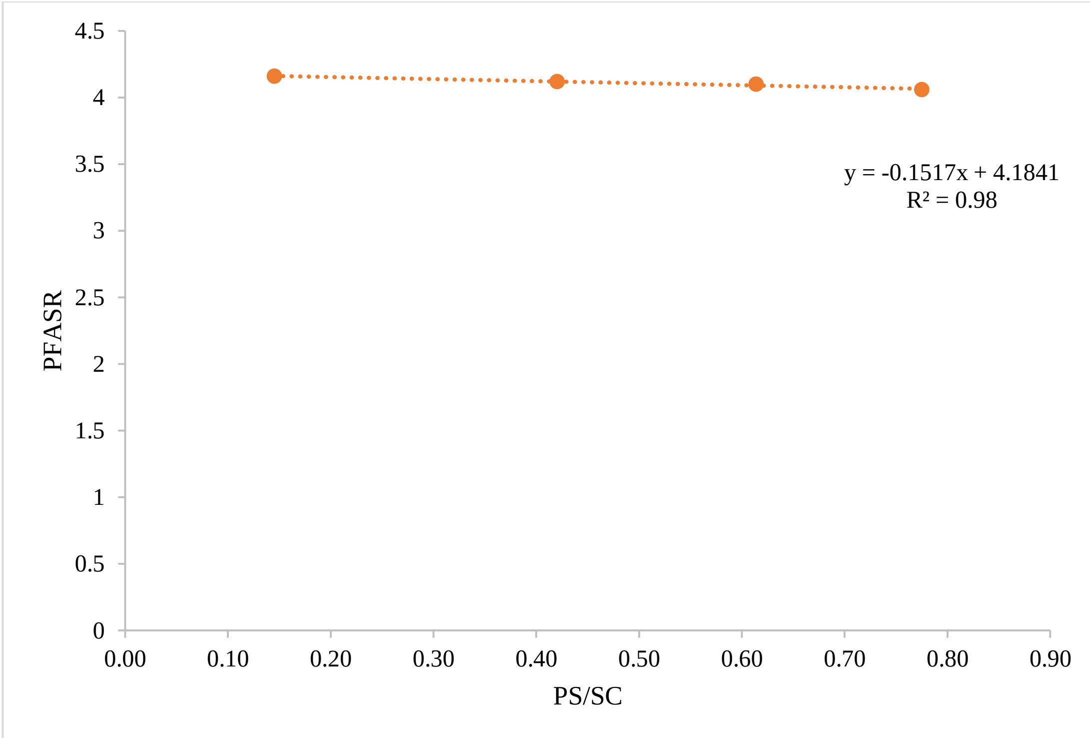


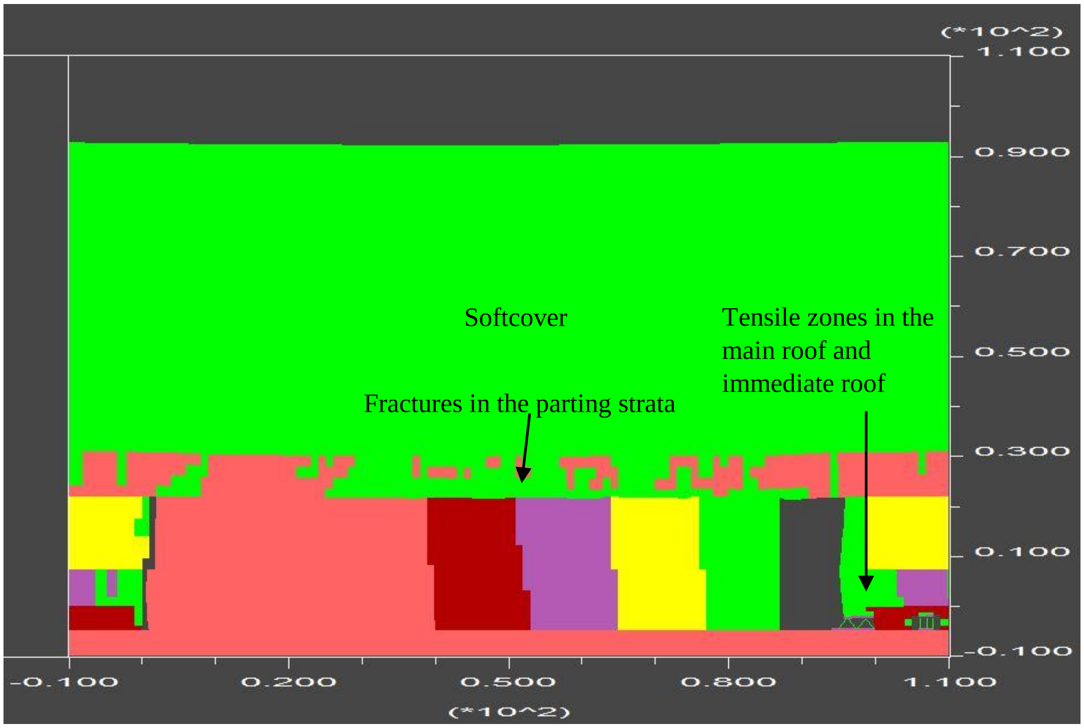
Fig. 6.7. Trend of PFASR with the increase in PS/SC

6.4 Bending Behaviour of Parting Strata and Stress Recovery in the Caved Goaf

The bending behaviour of the parting strata and recovery of vertical stress in the goaf material was evaluated for the conditions prevailing at Kuiya Colliery at the cover depth of 93 m. Four numerical models with the PS/SC ratio varying from 0.15 – 0.78 were studied to assess the influence of the softcover on the bending behaviour of parting strata. The thickness of parting strata varied from 9 – 31 m, while the softcover varied from 40 – 62 m. The periodic filling of goaf material was simulated during the main fall and the periodic caving till the cumulative face advance of 100 m. The initial properties of the strain hardening caved goaf material is assigned considering the caving height of 23.9 m and extraction height of 3 m. The corresponding bulking factor of the caved material was 1.125, and bulk density was 1899 kg/m^3. The initial tangent modulus of the goaf material was taken as 49.93 MPa, while the Poisson's ratio of 0.45 was considered to obtain the bulk and shear moduli following the standard relations. Figure 6.8a-d shows the disposition of the periodically filled goaf piles along with the fractures that developed in the parting strata upon the face advance of 100 m with different PS and SC conditions.

The PS/SC ratio of 0.15 had the PS of 9 m while the SC was 62 m thick. The PS developed numerous fractures in the goaf region. In this case, the strata ahead of the face also received tensile failure (Figure 6.8a). The sub-vertical fractures are observed at the centre with bending of strata over goaf piles behind the depillaring face. The higher loading at the goaf edge produced dead loading of the immediate and the main roof over the support. As the PS/SC increased to 0.42, a similar pattern of failure is observed in the 9 m thick lower parting strata, overlain by 11 m thick upper strata (Figure 6.8b). Although the fractures developed separately in the upper parting, they merged over the central portion of the goaf. The failure of the parting strata is quite concentrated in this case which indicates that the stiffness of the layer is still inadequate to develop a uniformly bending arch. The main roof developed distinct tensile failure over the goaf edge in this case.

With a further increase in the PS/SC ratio to 0.61, the fractures in the parting strata spread evenly over the exposed region in the goaf. The parting strata received lesser damage as characterised by the development of sparse tensile fracture planes as the 44 m thick softcover settles with bending of the 27 m thick parting strata comprising of 18 m thick upper and 9 m thick lower parting. The tensile failure zones still developed at the goaf edge (Figure 6.8c). At the highest PS/SC ratio of 0.78, the fractures in the parting strata propagate following a uniform pattern, quite similar to the ratio of 0.61. However, the bending of the parting strata is further controlled as reflected in terms of improved stability of the goaf edge (Figure 6.8d).



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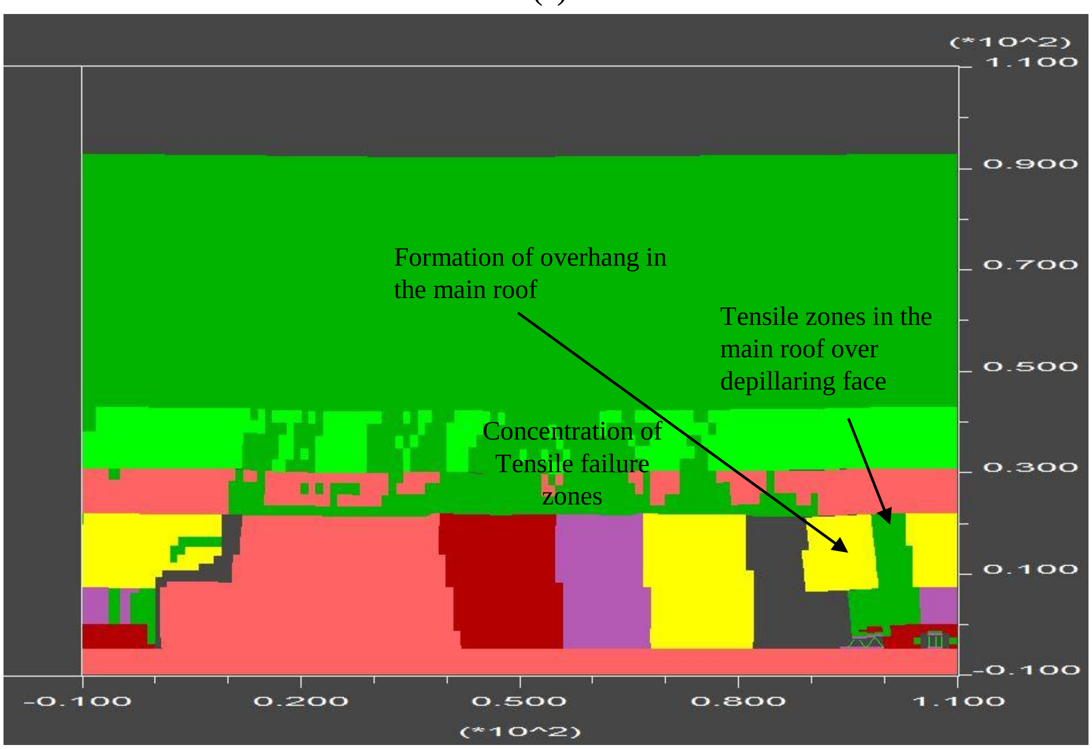

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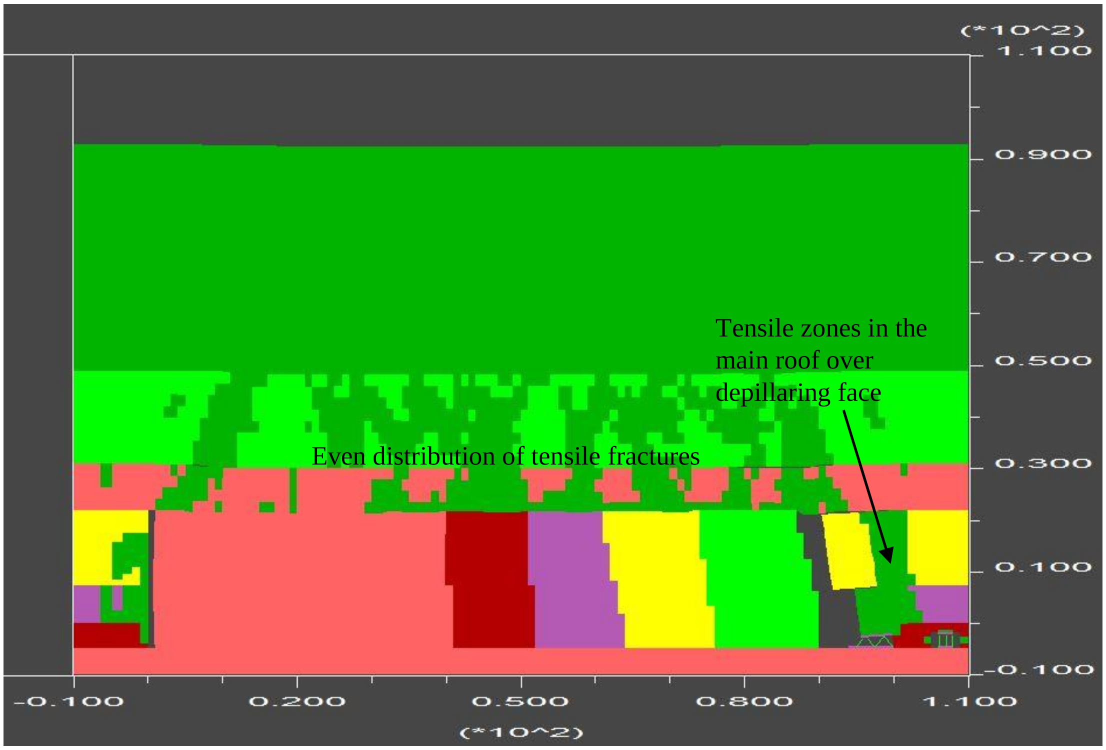

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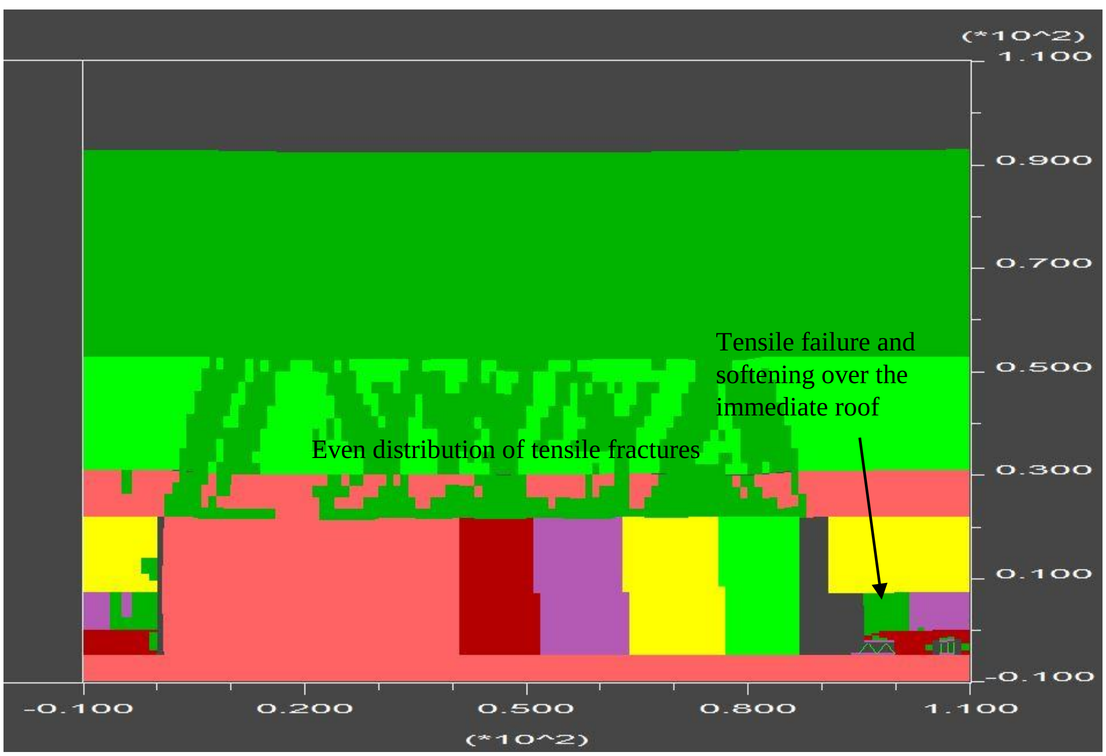

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Fig. 6.8. Periodic goaf filling in the depillaring working (a) PS/SC = 0.15, (b) PS/SC = 0.42, (c) PS/SC = 0.61, (d) PS/SC = 0.78

Table 6.3 shows the vertical stress that recovered in the goaf after the main fall for different PS/SC ratio at the cover depth of 93 m in the depillaring workings of Kuiya Colliery. The results show a very close stress recovery that varies 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.

Table 6.3. Vertical stress recovered after main fall at 93 m cover depth

PS/SC	0.15	0.42	0.61 (Actual)	0.78
Vertical stress recovery, MPa (% of in situ stress)	-0.98 (49)	-1.02 (49.9)	-1.03 (50.5)	-1.05 (51)

The cover pressure distance for PS/SC of 0.15 is 21 m from the goaf edge which is observed at 60 m of face advance. As the PS/SC increased to 0.78, the cover pressure distance increased to 31 m which is observed at 71 m of face advance. For the field representative condition where the PS/SC ratio is 0.61, the cover pressure distance of 28 m is obtained at 67 m face advance.

Figure 6.9 shows the profile of vertical stress recovery in the goaf for the minimum and the maximum PS/SC ratios. The general trend of the plot is quite similar, indicating a marginally higher recovery of the vertical stress in the case of the higher PS/SC.

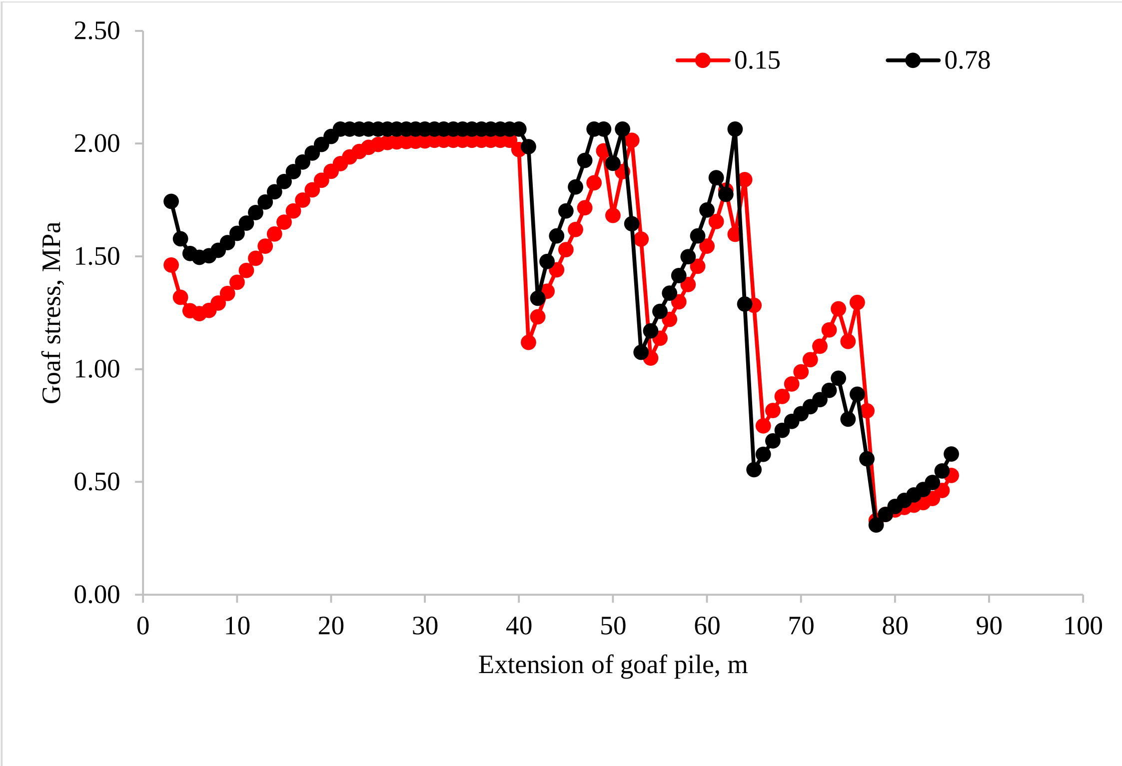

Fig. 6.9. Goaf stress recovery in Kuiya working at the cover depth of 93 m, PS/SC= 0.15, 0.78

The settlement behaviour of the 9 m thick loading layer was studied to evaluate the effect of the PS/SC ratio on the settlement pattern of the PS and the SC. Figure 6.10 shows the settlement trend of the parting for the minimum and the maximum values of the PS/SC. The maximum settlement of 1.18 m was observed for the minimum PS/SC of 0.15. Conversely, the minimum settlement of 0.67 m was noted 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.

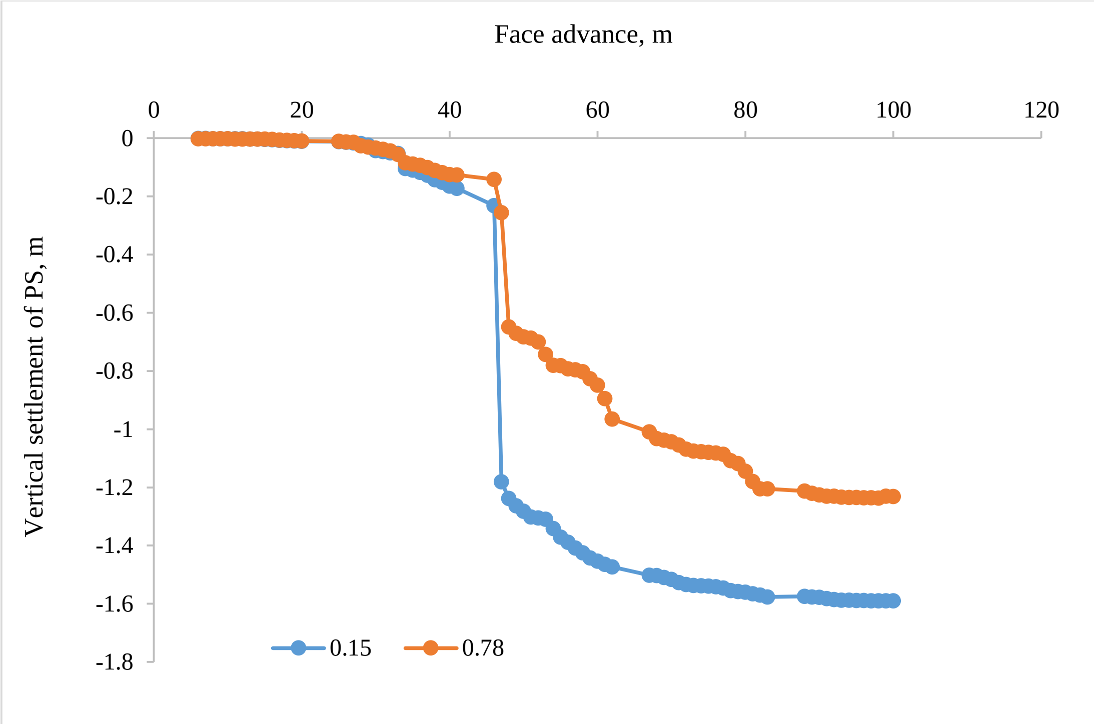

Fig. 6.10. Settlement of PS with progressive face advance in Kuiya Colliery working, PS/SC = 0.15, 0.78

6.5 Assessment of the Safe Parting Thickness

The assessment of the safe parting thickness has been done based on the design criteria as discussed in the previous chapter. The plot of the maximum goaf edge convergence slope (MGECS) as a function of the PS/SC ratio (Figure 6.11) shows a decreasing trend of the MGECS in the range of 99 – 76 mm/m of face advance for the PS/SC ratio varying from 0.15 – 0.78. For the maximum allowable goaf edge convergence slope of 75 mm/m, the safe PS/SC ratio of 0.74 is estimated for prevailing field conditions. The minimum thickness of the parting strata for safer depillaring below the cover depth of 93 m having 44 m thick softcover, is estimated as 32.6 m.

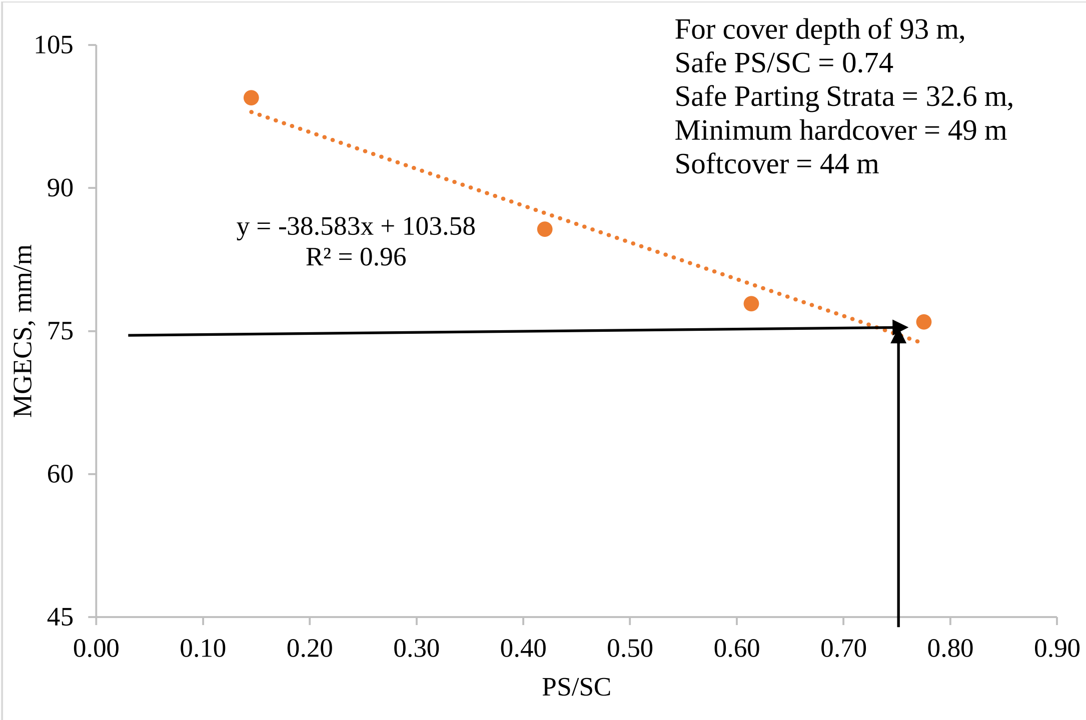

Fig. 6.11. Plot of the MGECS vs. PS/SC for Kuiya Colliery depillaring working

Figure 6.12 shows the plot of the peak settlement rate (PSR) of the parting strata for varying PS/SC in the geo-mining condition prevailing at Kuiya Colliery. With the increase in the parting strata from 9 to 31 m and simultaneous reduction of softcover from 62 to 40 m, the PSR decreases from 949 – 176 mm/m of face advance. The trend line of the PSR also confirms that the settlement rate of the parting strata is almost stabilised at PS/SC of 0.74. The threshold PSR of 166 mm/m was obtained for the safe PS/SC of 0.74 for the prevailing conditions.

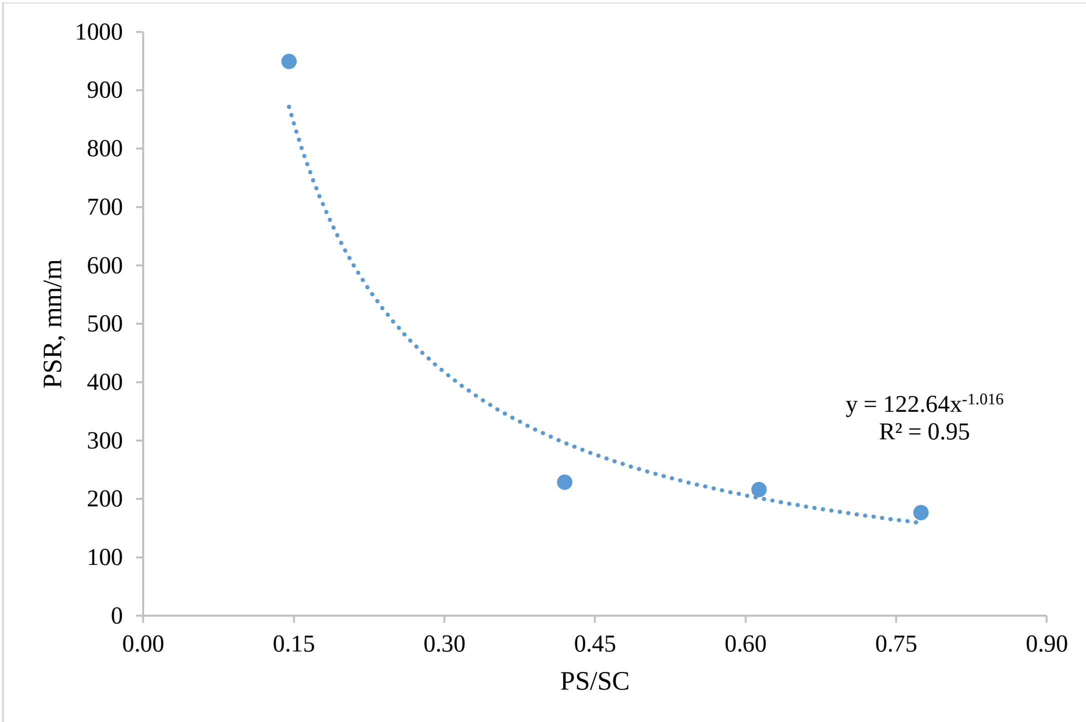

Fig. 6.12. Peak settlement rate of the parting strata for different PS/SC at Kuiya Colliery

Figure 6.13 shows the location of failure in the parting strata behind the goaf edge for different PS/SC ratios. The non-linear increasing trend of failure location from the goaf edge shows a distance of 25 m corresponding to the safe PS/SC ratio of 0.74.

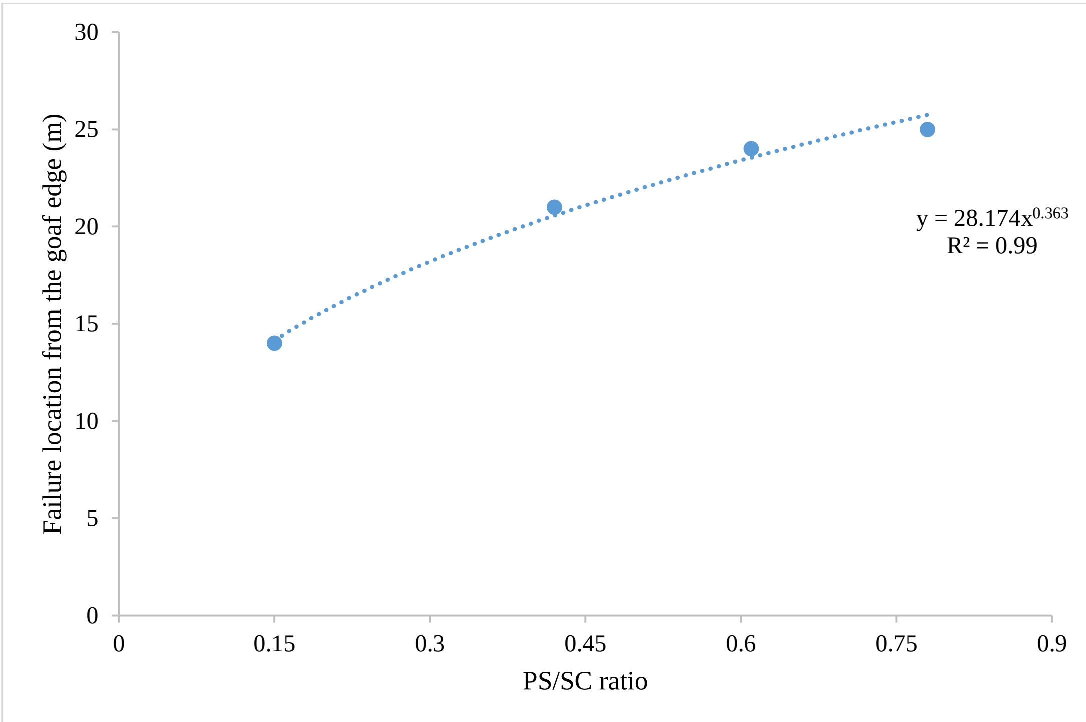

Fig. 6.13. Location of the failure for different PS/SC

6.6 Estimation of the Optimum Support Capacity

A parametric modelling study for support capacity of 2 × 200 t, 400 t and 600 t was done to evaluate the support performance in the actual field conditions having softcover of 44 m and hardcover of 49 m. The hardcover comprised of 22 m of caving zone and 27 m of parting strata. The comparative plot of the load on the supports (Figure 6.14) shows that the load on the support increases with an increase in the capacity of the goaf edge support during the progressive face advance. The support of 200 t undergoes frequent yielding for a longer period during the progressive depillaring. With the increase in capacity of the hydraulic goaf edge support, the yielding tendency of the support reduces, but it induces a comparatively higher load.

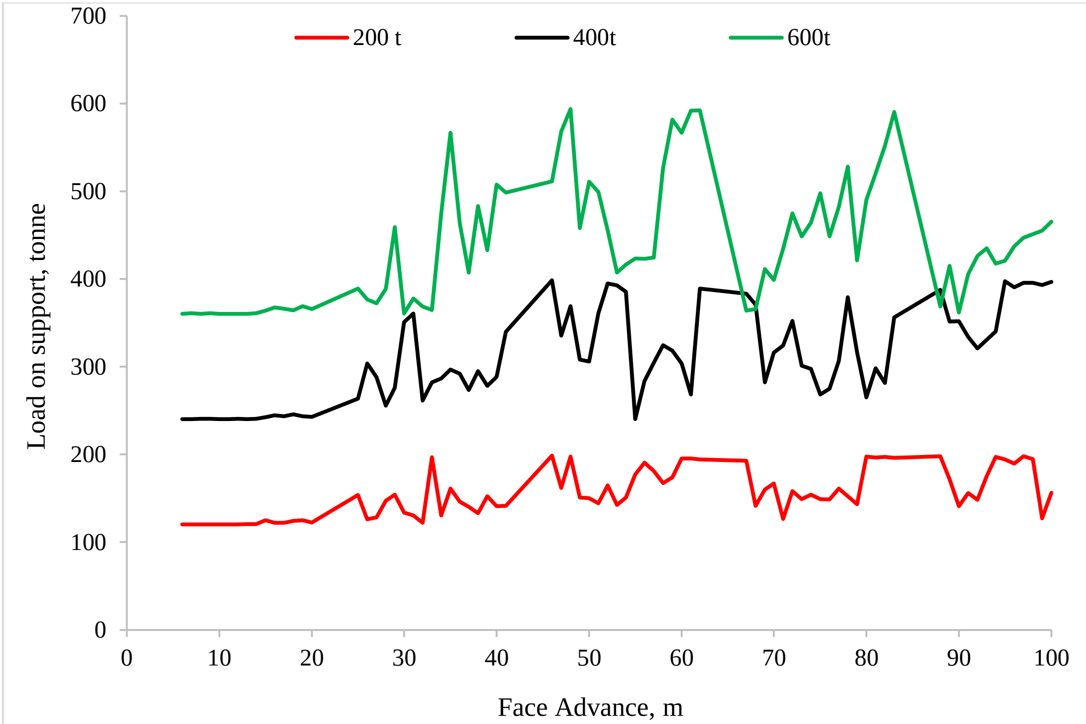

Fig. 6.14. Load on the support during progressive depillaring with different support capacity

Considerably increased maximum values of goaf edge convergence slope are observed frequently in the progressively worked depillaring working while deploying mobile goaf edge support of lower capacity (Figure 6.15). With the increase in capacity of the support, the maximum convergence values undergo significant reduction.

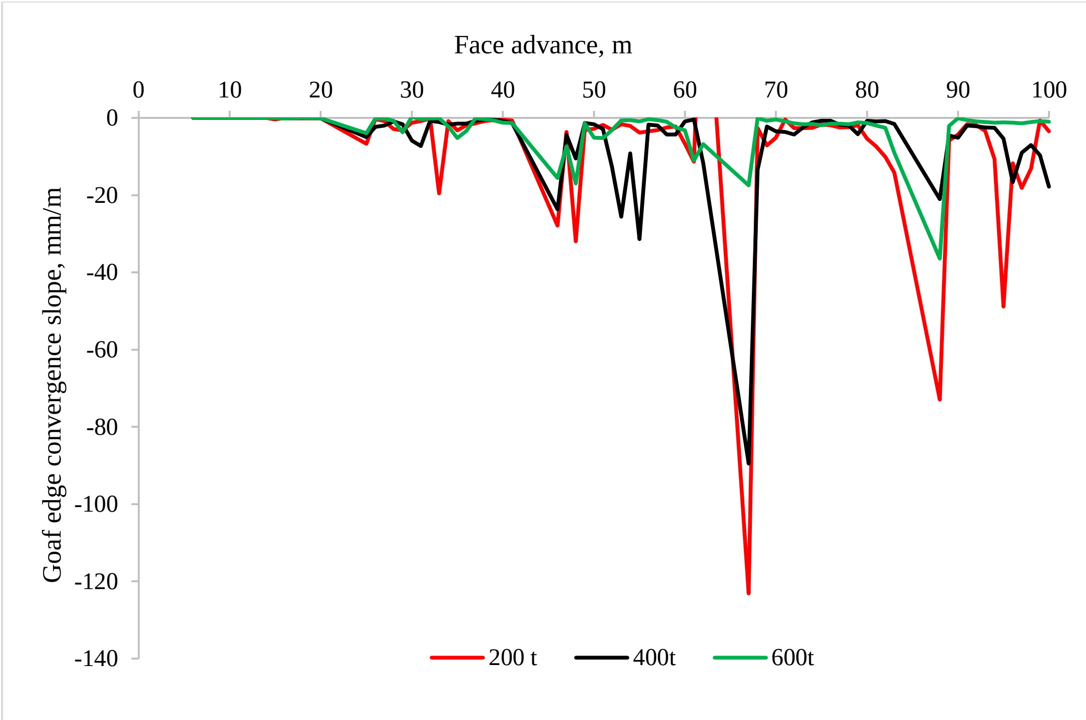

Fig. 6.15. Goaf edge convergence with the progressive face advance for different support capacity

The plot of the maximum goaf edge convergence slope for different capacities of the goaf edge support shows that for the increase in support capacity from 200 t to 600 t, the maximum convergence reduces from 123 mm/m to 36 mm/m. The straight-line trend obtained on the basis of a limited range of data shows that the optimal capacity for safer depillaring in the given condition is 2 × 437 t (Figure 6.16).

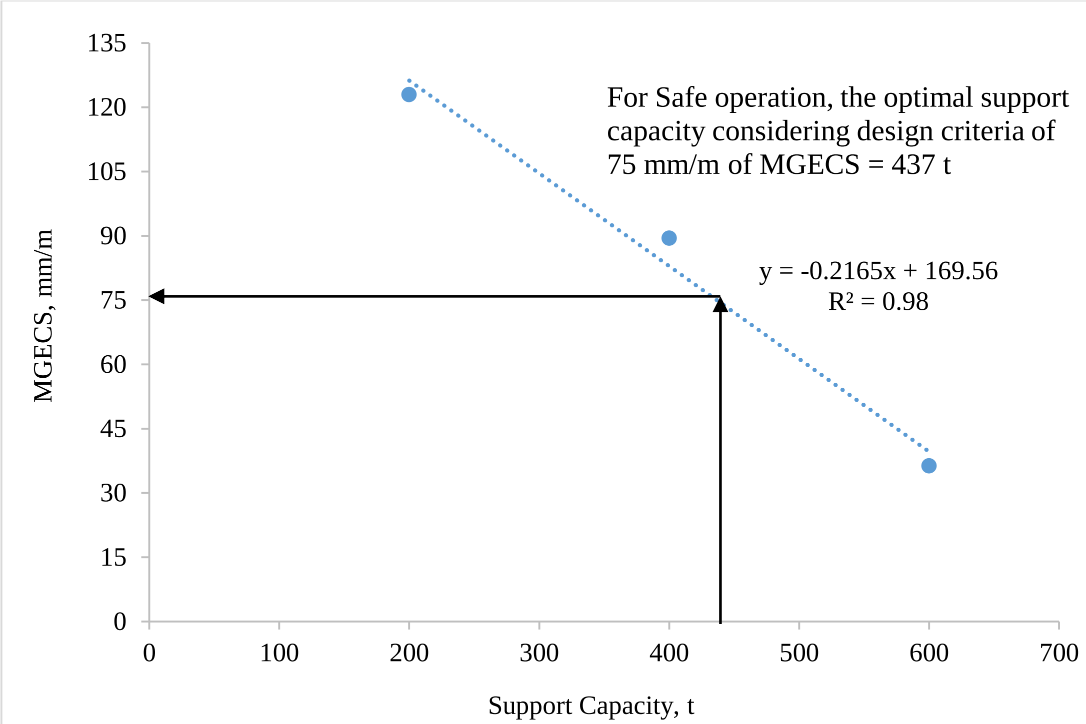

Fig. 6.16. Maximum goaf edge convergence vs. Support capacity

6.7 Three Dimensional Modelling

A three-dimensional modelling of the depillaring working under the softcover at Kuiya Colliery was done to evaluate the effect of the diagonal line of extraction on the front abutment loading and the caving behaviour of the strata in the working. The findings could be compared with the plane strain modelling results to find out the best suitable orientation of the goaf line.

The three-dimensional modelling study was conducted using the Finite-Difference software FLAC 3D (Itasca, 2015). It used the same geo-mining and strata details as the plane strain model. The mining zone in the model replicated the panel size of the depillaring panel. The side boundaries of the model were decided to comply with the requirement of the infinite elastic boundary. The left and right side boundaries along the x-direction were kept at '2a' distance for the planned extraction of length ‘a’ in the panel. Similarly, the side boundaries along the y-side were kept at '2b' distance for the planned extraction across the face of length ‘b’.

The discretisation scheme of the three-dimensional model was similar to the two-dimensional plane strain model. The element size of all the strata within the mining zone was 1 m in the X and 0.75 m in the Y-directions. However, the zone size was increased in both the X and the Y directions following the geometrical progression ratio of 1.17 in all the four side boundaries outside the mining zone. In the vertical Z direction, the size of elements in the coal face was kept as 0.43 m, while the element size of rock layers was increased by a geometrical progression ratio of 1.1. In this process, due care was taken to ensure that the zone size of the strata remained almost similar to the plane strain model. For the cover depth of 93 m, the interface stiffness of 45 MPa/m along with other pertinent properties similar to the 2D model was taken for simulating the major parting planes. The initialisation of the virgin in situ stress and the boundary condition was also similar to the plane strain model. The constitutive model for different strata was also the same, but it was implemented in the 3D model with different sub-routines specifically prepared for FLAC 3D. Figure 6.17 shows the plot of the in situ 3D model of the Kuiya Colliery working.

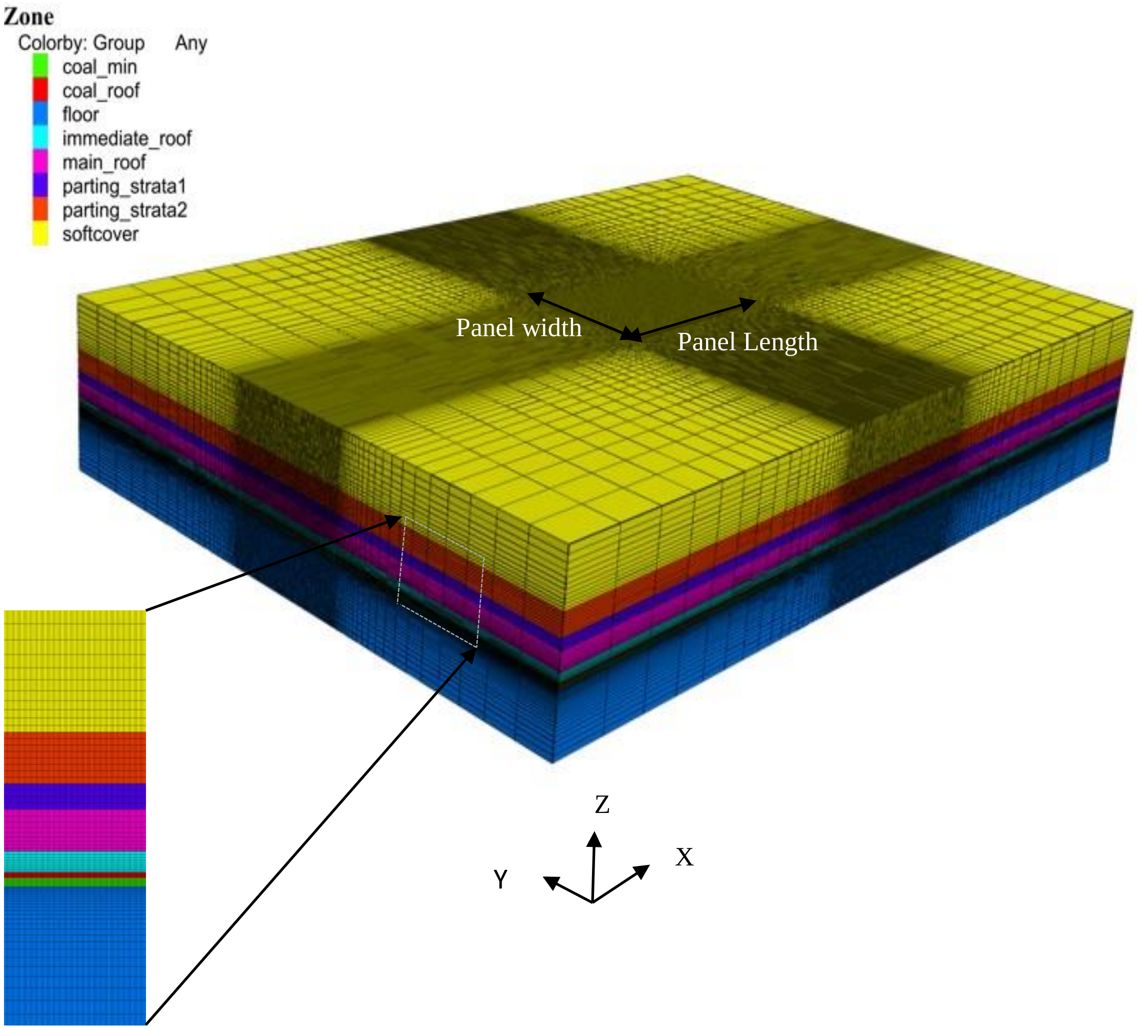

Fig. 6.17. Three dimensional model of Kuiya depillaring working

The three dimensional model of the mine considered development over 120 m of panel width and 180 m of panel length as prevailing in the field. The developed working has a gallery of 4 m and 3 m height forming pillars of 21 × 21 m from centre to centre. The origin (0, 0, 0) has been taken at the coal roof, marking the galleries that form the panel boundary (Figure 6.18).

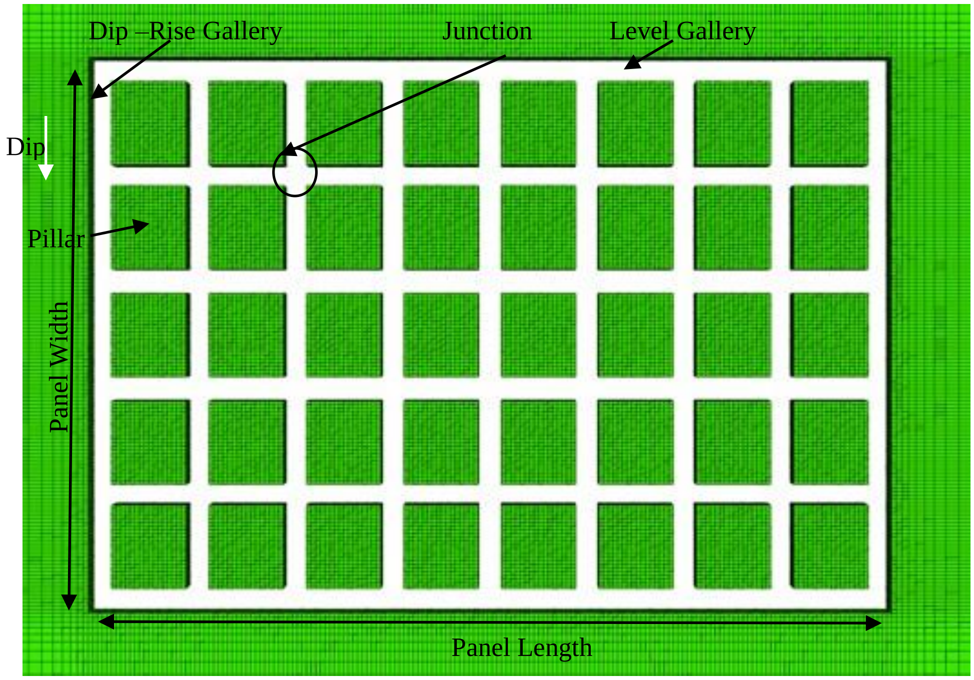

Fig. 6.18. 3D model of the developed panel

The depillaring operation was simulated following the diagonal line of extraction (Figure 6.19). The algorithm for calculating the elastic and elasto-plastic roof-floor convergence at the centre of the diagonal line of extraction was adopted from the plane strain model. The softening zones were monitored for shear and tensile modes of failure, similar to the plane strain model formulation. The fractured zones in the parting strata were simulated by assigning a reduced modulus of 0.5 times the original modulus in all those elements which experienced tensile failure. This value was worked out upon calibration of the model and has been used in a number of models consistently producing field representative results. The tensile fracture so simulated was checked in the strata layers below the softcover and outside the panel boundaries as well. Softening of strata that received shear mode of failure was simulated by reducing its cohesive strength to 20 % of the peak value. The progressive depillaring following the diagonal line of extraction was simulated in the stage of 1 m of advance in the direction normal to the diagonal line at each stage of mining in the depillaring panel.

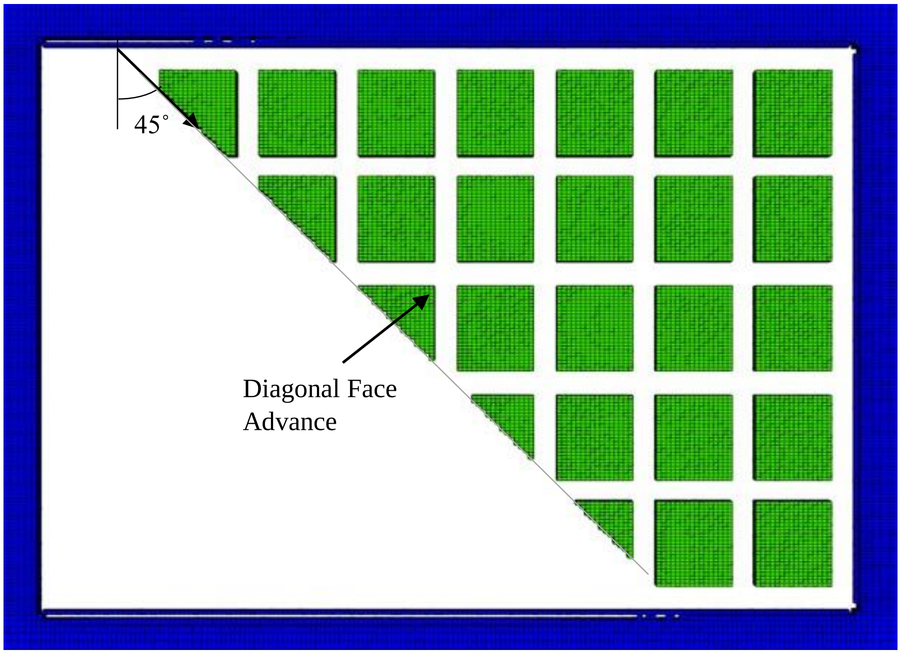

Fig. 6.19. Numerical model showing the diagonal line of face advance

The modelling results showed that the maximum front abutment stress of 14 MPa developed during the progressive depillaring at the diagonal face advance of 97 m. The abutment stress was concentrated at the centre of the remnant pillar in the first row that lies very close to the diagonal line of face advance (Figure 6.20). The abutment stress in the second row of the pillars was lesser than the first row near the diagonal line. Altogether, three rows of pillars were under the effect of abutment stress. The influence zone of the front abutment stress was extended up to 42 m from the diagonal line.

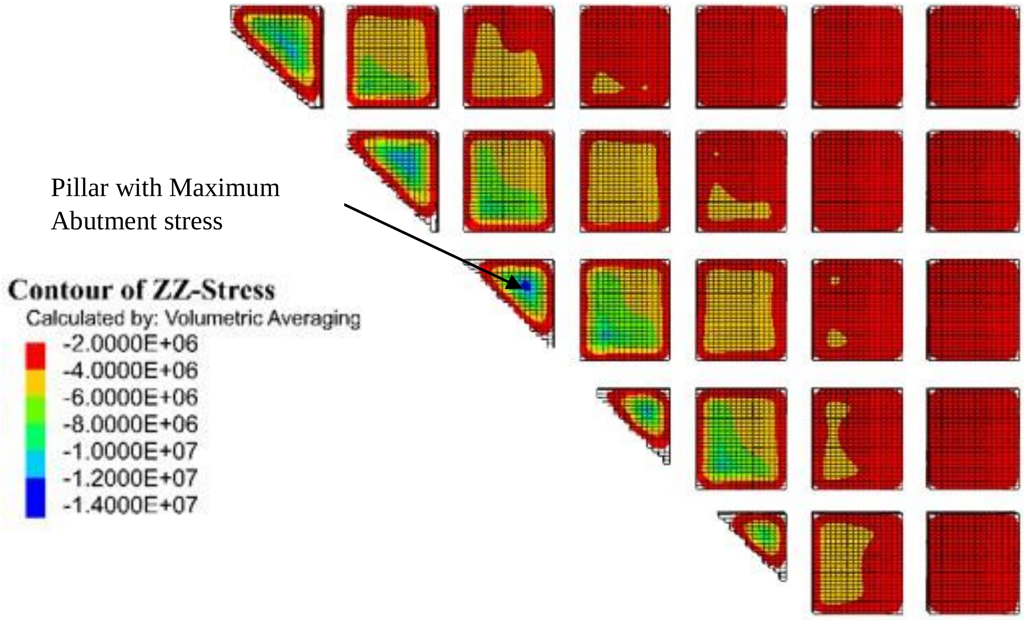

Fig. 6.20. Front abutment stress at 97 m face advance

Figure 6.21 shows the state of failure in the pillars at the maximum abutment load (Figure 6.20). Shear mode of failure was prominent. The failure was severe in the pillar located near the centre of the diagonal line. The core of the partially extracted pillars near the goaf line also showed failure in shear but it was prone to relax upon release of the stress. Although the second row of pillars from the diagonal line of extraction had their core intact, their edges and sides received unrecoverable failure under the shear mode. The central pillar P2 in the second row also received failure in a similar mode, highlighting the challenging loading condition in this region.

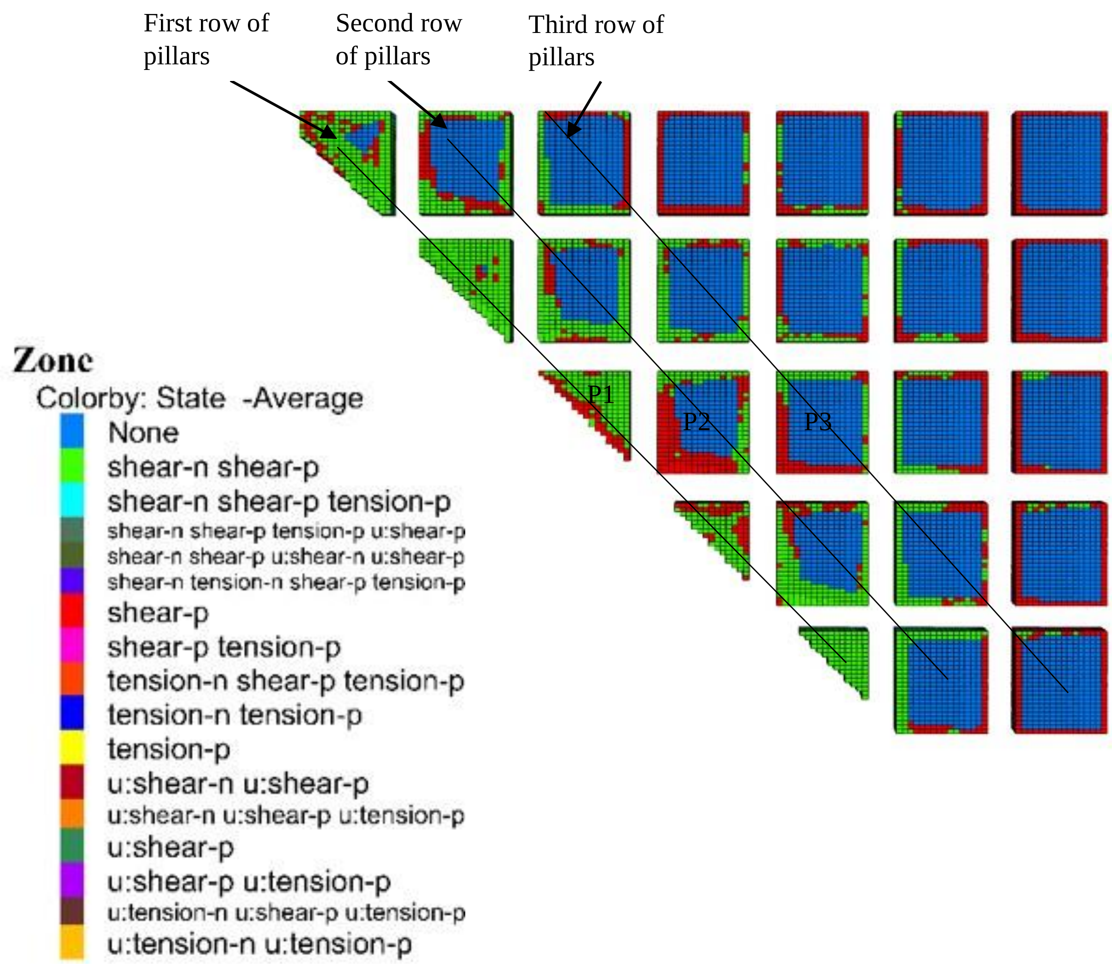

Fig. 6.21. Failure state in the pillars at 97 m face advance

The extent of the failure zones in the third row of pillars was considerably less as these pillars were relatively subjected to lesser abutment stress as compared to the first and second rows. However, the central pillar of this row was still affected due to the shear failure along the sides.

Figure 6.22 shows the caving profile of strata upon main fall in the goaf, as observed at 104 m of the diagonal line, which corresponds to the area of goaf exposure of 10,000 m^2. The caved area formed the typical shape of an ellipse with the major axis oriented parallel to the diagonal line. The lateral extent of the caved zone in the immediate roof was larger, but it reduced in the upper zone of the strata. The plot obtained along section line AA' (Figure 6.23) shows an almost symmetrical caving profile extending up to the base of the 9 m thick lower parting strata. The front abutment stress in the pillars relaxes upon the occurrence of the main fall.

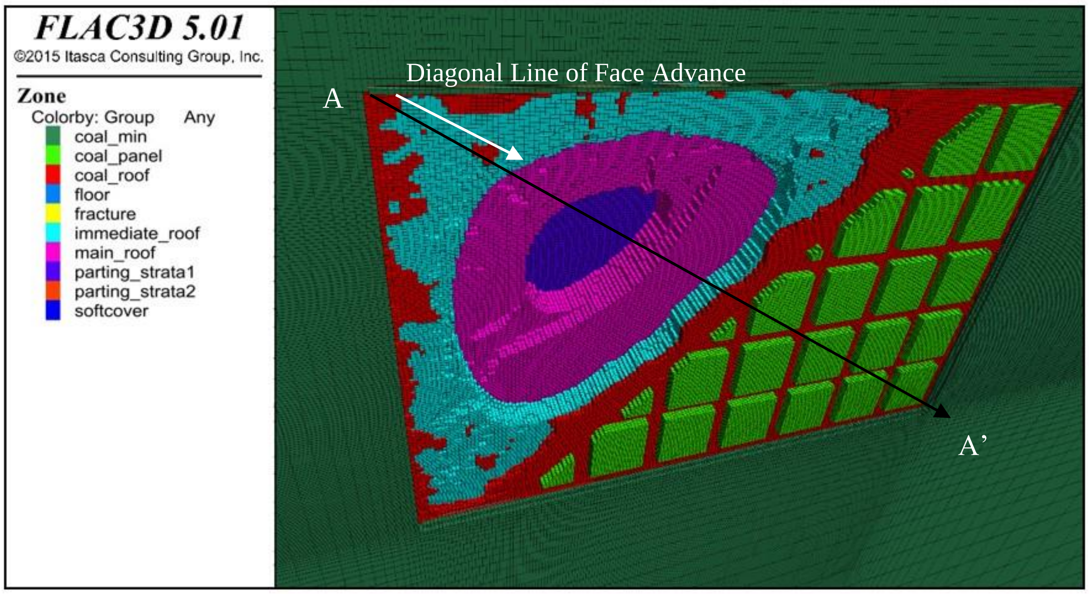

Fig. 6.22. Main fall at 104 m of the diagonal face advance

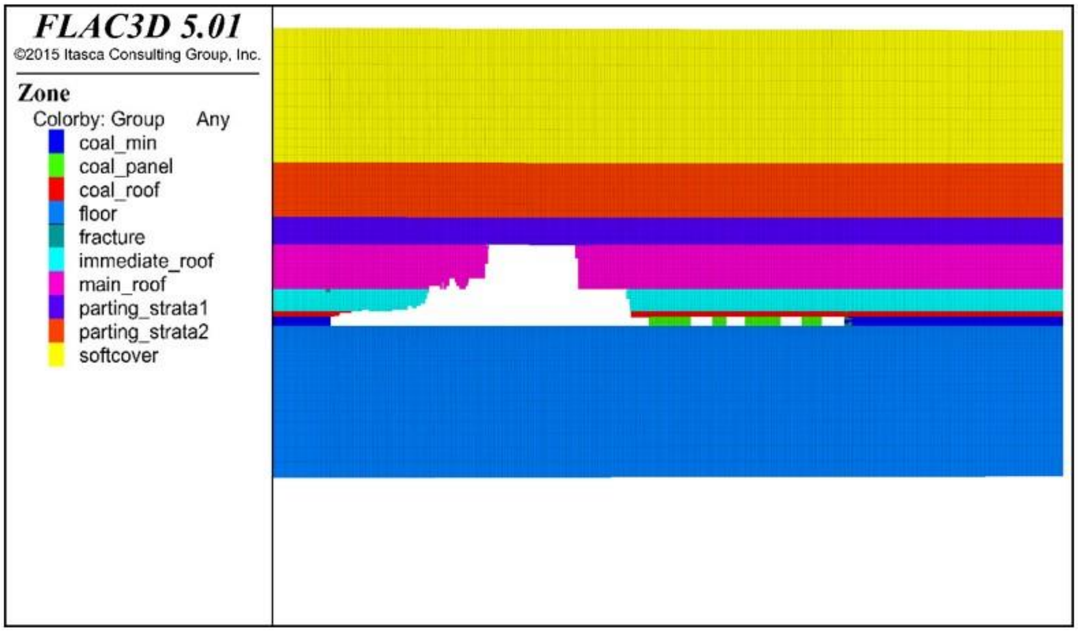

Fig. 6.23. Caving profile of strata along the section line AA'

6.8 Summary

This chapter dealt with validating the numerical modelling approach to assess the influence of softcover on the caving behaviour of strata in a depillaring working at a cover depth of 93 m having a softcover component of 44 m. It delineated the safe thickness of the parting strata and the goaf edge support requirement for the given working. The parametric study of the effect of the PS/SC ratio on the span of the main fall and the front abutment stress showed a similar trend as observed in the parametric study. The caving span increased with the increased PS/SC ratio, while the abutment stress decreased with the increased PS/SC ratio.

In the case of a lower PS/SC ratio, the parting strata showed a faster bending tendency indicating inadequate stiffness to resist the dead load of the softcover. The parting strata failed significantly closer to the goaf edge in this case. The failure in the parting strata was also highly concentrated in this case. On the other hand, a higher PS/SC ratio ensured a safe working condition as the fractures in the parting strata were evenly distributed, which indicated adequate bending stiffness to resist the settlement of the softcover. The failure location of the parting was also noted away from the goaf edge in this case.

Although the caved goaf achieved the cover pressure in all the simulated cases, the cover pressure distance was the lowest for the minor PS/SC ratio. The settlement rate of the parting strata was the highest in this case. With increasing PS/SC, the cover pressure distance increased while the maximum goaf edge convergence reduced, indicating a significant contribution of the failure location on the severity of load transfer at the goaf edge. The safe PS/SC ratio of 0.74 was obtained for the depillaring working at Kuiya Mine, corresponding to the maximum allowable convergence slope of 75 mm/m at the goaf edge. The safe thickness of the parting strata was estimated as 32.6 m for the softcover of 44 m at the cover depth of 93 m in the field. The threshold value of PSR was 166 mm/m for the safe PS/SC delineated in this case. The safe distance of failure of the parting strata was estimated as 25 m behind the depillaring face.

The optimum capacity of the goaf edge support was selected based on the modelling-based observation of the maximum convergence slope at the goaf edge vs the support capacity. The support capacity of 2 × 437 t was estimated as the optimum for efficient roof control at the goaf edge in the depillaring working with a parting thickness of 32.6 m and a softcover of 44 m.

In the actual geo-mining condition, the parting strata is only 27 m thick, which is marginally lower as compared to the minimum safe value. Although it would fail at 23.5 m behind the goaf edge, the estimated peak settlement rate is 202 mm/m, which is 21.7 % more as compared to the desired rate for safer negotiation of the weighting periods. Under such conditions, the goaf edge support having an optimal capacity of 437 t may experience larger than the nominal closure and extended yielding period along with relatively increased convergence in nearby junctions and spalling of pillars.

The results of the 3D model showed the quite delayed occurrence of the main fall for depillaring following the diagonal line of extraction. The main fall was observed at 104 m of diagonal face advance with peak front abutment stress of 14 MPa. In the 2D plane strain model, the main fall occurred at 40 m of face advance with peak abutment stress of 8.4 MPa. The comparative analysis of the two conditions shows that the straight line of extraction provides a better condition for easier caving of the strata and lesser stress concentration in the working as compared to the diagonal line working.