Chapter 4

FIELD STUDY

4.1.General

Three cases of Indian coal mines adopting mechanized depillaring operation has been selected in the study for validation of the numerical model. The pillar width in the selected panels was 26 m, 35 m, and 45 m. The extraction pattern for the pillar width of 26 m was fish-bone, whereas for pillar width of 35 m and 45 m, the extraction pattern is split and fender, and double split and fender, respectively. Three-dimensional numerical simulation techniques have been used in the study for simulating the selected panels sequentially using the numerical modeling software, *FLAC*^{3D}. The simulation results were obtained for all the cases in terms of vertical stress and yield profile at the mid-level of the pillars. The numerical models have been validated using field observation during the depillaring operation and strata instruments.

4.2.Case A

The bord and pillar panel of Case A belongs to a coal mine of Godavari Khani Coalfields. The mine is located in Telangana's Peddapalli district under Singareni Collieries Company Limited (SCCL). The latitude and longitude of the mine were about 18ºN and 79ºE, respectively. The working seam (Coal seam No. 1) is present in the panel at a depth of about 180 m - 220 m. The seam inclination is 1 in 9 towards N 60º E, and the thickness varies from 5.0 m to 6.25 m. A thick bed of fine-grained sandstone of about 26 m is present as immediate strata. Fig. 4.1 shows the borehole log of the strata in the considered panel. The panel has been developed in the middle section of the coal seam with six heading using conventional mining techniques (drill and blast). The average width and height of the galleries in the panel were 3.5 m and 3.0 m. The panel consists of a 5 x 10 array of pillars with an average dimension of 26 m X 26 m (center to center). The average length and width of the panel were about 310 m and 180 m, respectively. A completely extracted panel was present on one side of the considered panel, whereas a developed panel was present on the other side. Fig. 4.2 shows the typical layout of the panel.

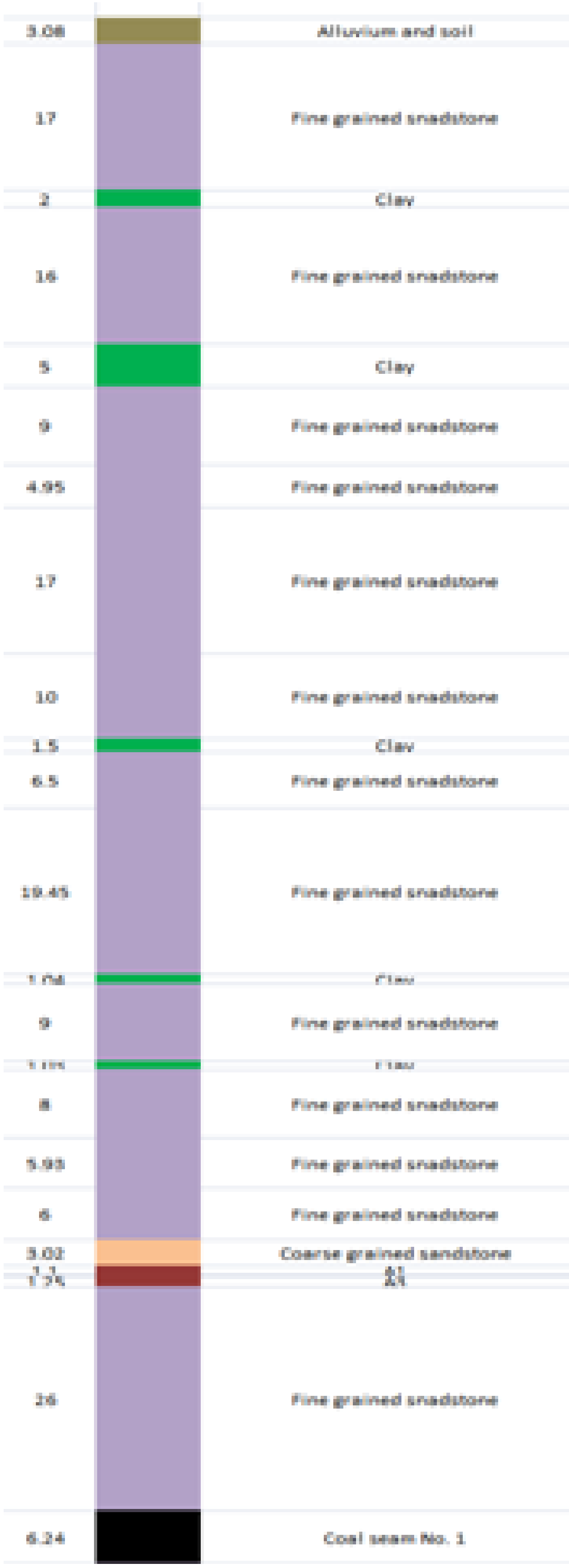


Fig. 4.1 Borehole log of the strata in ‘Case A’

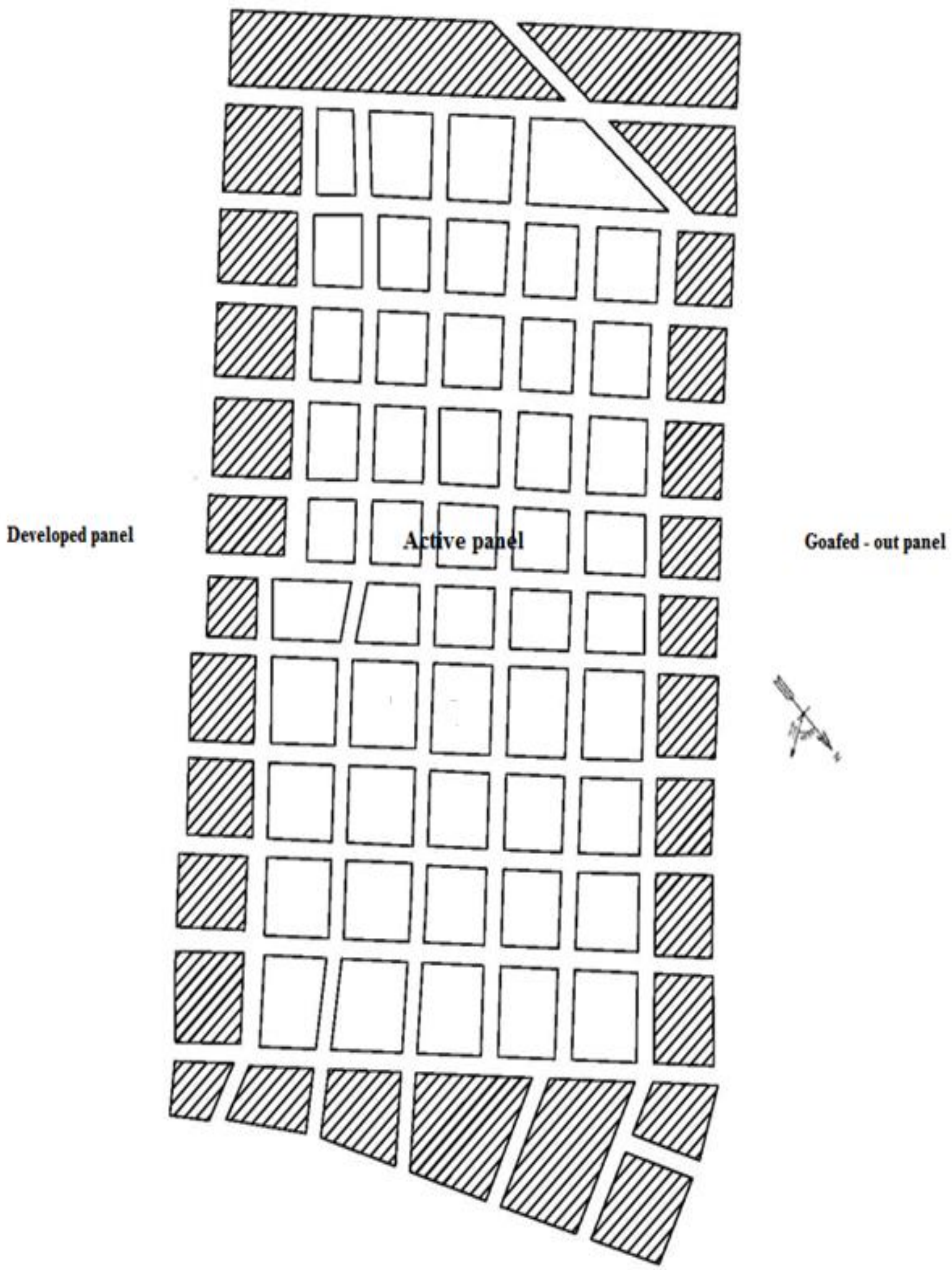
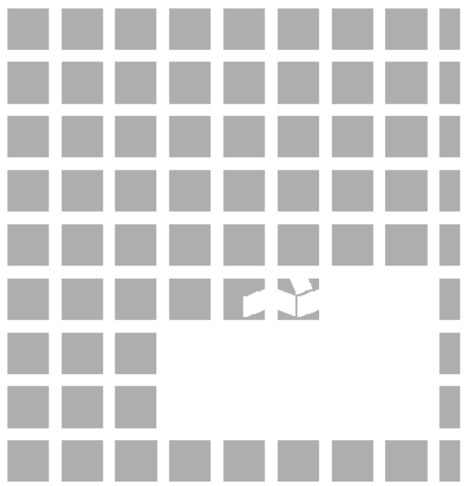


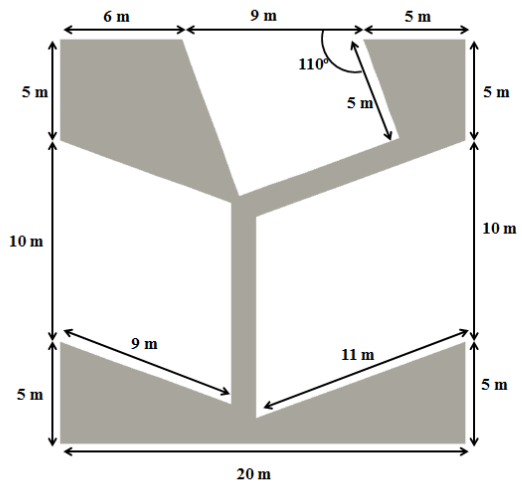
Fig. 4.2 Layout of the panel in ‘Case A’

4.2.1. Depillaring operation in ‘Case A’

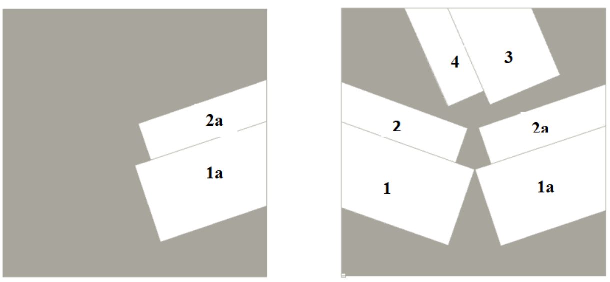
The depillaring operation has been commenced in the panel using *CM* technology, adopting a straight line of extraction. The galleries were widened from 3.5 m to 6.0 m for easy maneuvering of the machine and heightened from 3.0 m to 4.5 m. The pillar size after widening and heightening the galleries becomes 20 m x 20 m (corner to corner). The panel adopts the fish-bone pattern of extraction during the final extraction of coal. The pillars have been sliced from three sides, leaving an in-bye rib of about 5 m before slicing. The slicing angle was about 70º. The width of the final snook was about 5.5 m. Fig. 4.3 shows the panel's typical layout and pillars under extraction.



a. Plan view of the panel



b. Zoomed view of the working pillar



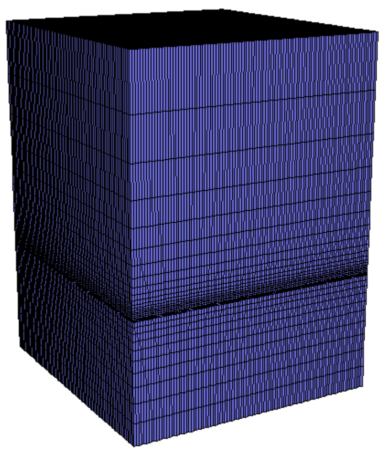
c. Slicing sequence of pillars

Fig. 4.3 Typical layout of the depillaring panel and extraction pattern in ‘Case A’

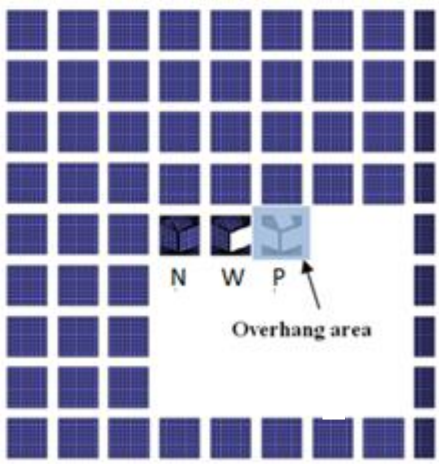
Fig. 4.3a shows the plan view of the panel at a depillaring stage where two and a half rows of pillars were extracted. Fig. 4.3b shows a typical structure of the remnant pillars after complete slicing. The slicing operation was performed in two consecutive pillars simultaneously in this extraction pattern, and the sequence of slicing follows slice 1 - slice 2 - slice 1a - slice 2a - slice 3 - slice 4, as shown in Fig. 4.3c.

4.2.2. Numerical simulation for 'Case A'

A three-dimensional numerical model of the panel having a sufficiently large size has been prepared in the study to assess the stability of the structures (pillars/remnants) during the depillaring operation. The panel has been constructed using brick elements, which comprise coal pillars, roof, and floor. Fig. 4.4 shows the discretized view of the model. Fig. 4.4a shows the three-dimensional view of the model, and Fig. 4.4b shows the plan view at the mid-level of the coal seam for a typical depillaring stage.



a Three - dimensional view



b Plan view

Fig. 4.4 Discretized view of the model in 'Case A'

The panel consists of a 9 x 9 array of pillars (i.e., nine pillars along the width and nine pillars along the length), including pillars of the nearby developed panel and the barriers. The barrier pillars towards the goaf side have been constructed half the pillar size to obtain the actual loading conditions. The pillar size has been taken as 20 m x 20 m (corner to corner), whereas the width and height of the galleries in the models have been considered as 6.0 m and 4.5 m, respectively. A highly discretized structure generally requires a large computational time, which is practically not feasible. Thus, the pillars are discretized into ten parts zones along the length and width of the pillar using brick elements considering the computational time. The discretization of the pillars has been formed using graded mesh where sides are finely discretized than the core. The model has been discretized into more than 2,70,000 elements. The roof and floor of the model has been discretized into 100 parts in x direction and 90 parts in y direction. The roof and floor have been discretized into 15 and 10 parts in z direction (along depth), respectively. The discretization ratio (for generating graded mesh) of the roof and floor have been taken as 2.5 and 0.5, respectively, so that final mesh has been generated close to the coal seam.

The fish-bone pattern of extraction has been adopted for slicing the pillars. The working pillar (Pillar W), previously extracted pillar (Pillar P), and the next pillar (Pillar N), was constructed in the model such that slices can be taken out from three sides of the pillar at different stages of depillaring. The slicing angle has been taken as 70°. Fig. 4.4b shows the typical depillaring stage concerning the focused pillars, i.e., the last extracted pillar (‘P’), the working pillar (‘W’), and the immediate next pillar (‘N’). An immediate stratum of 4.5 m was incorporated in the model above the pillars/remnants, forming a cantilever up to the last extracted pillar (‘P'), considering the field observations. The nodes of the coal pillars and ribs/snook in the model were attached to the overlying strata. The main strata have been constructed above the overlying strata up to the surface level considering the depth of cover as 200 m. The overlying strata and the main strata have been separated in the model using an interface. The materials properties used for coal, roof, and floor have been taken in the model as derived through the calibration process (Chapter 3). The specimen of the coal has been tested for *UCS* in the laboratory. It is determined as 46.8 MPa. The peak cohesion value has been determined using Eq. 3.3 (Chapter 3). The strength parameters for coal used in the model have been shown in Table 4.1. The sides of the model have been restricted in lateral directions and the bottom in the downward direction.

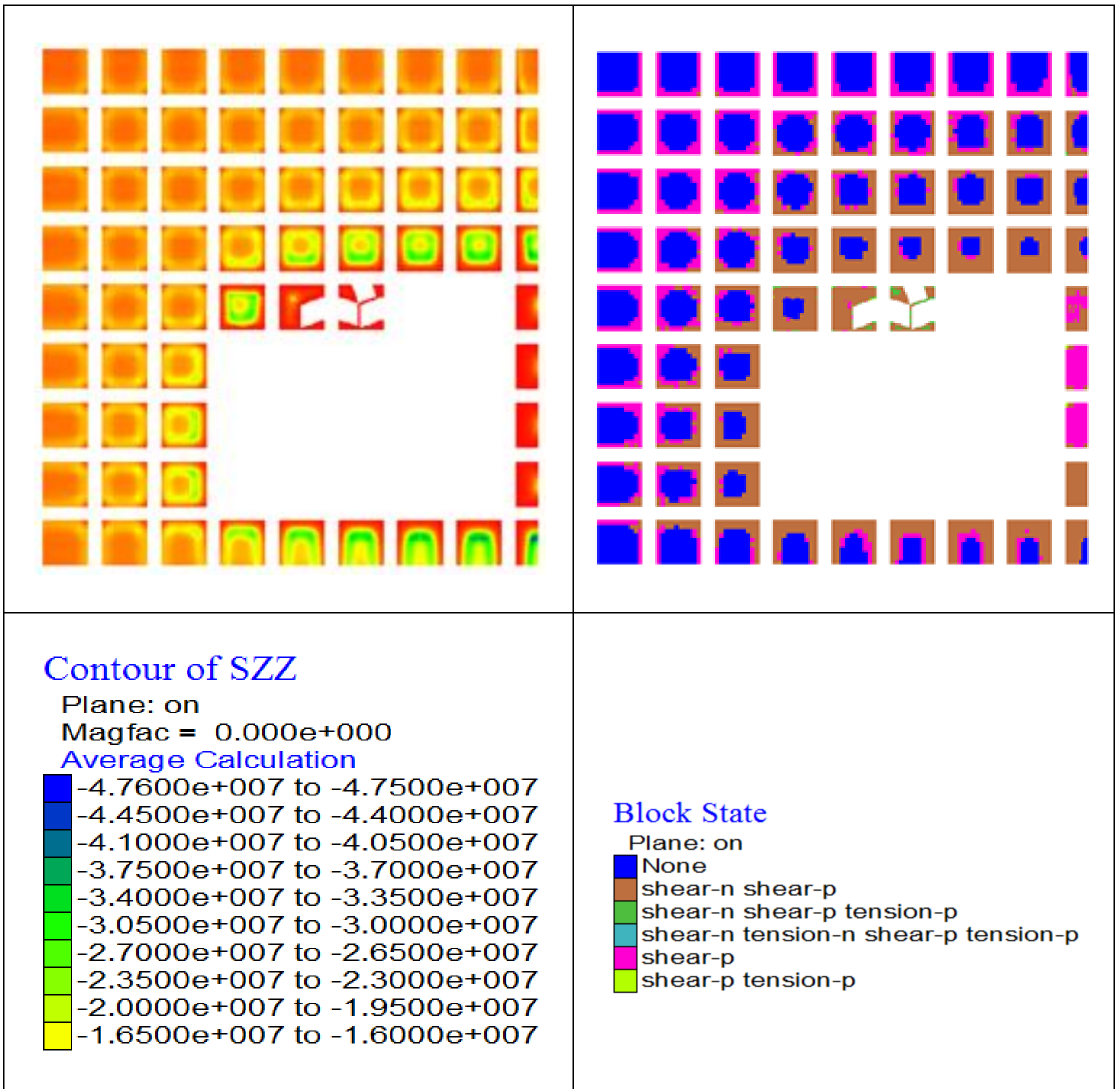
Table 4.1 Strength parameter for coal used in the model for 'Case A'

Shear strain (m)	**Cohesion (MPa)**	**Friction angle (°)**
0	1.75	30
0.005	1.16	30
0.015	0.58	30
0.03	0.29	30
0.1	0.09	25

The model has been simulated sequentially with a straight line of extraction. As discussed earlier, the maximum stress conditions on the pillars were observed on the depillaring stage, at which the advancement length is equivalent to the panel width. Thus, the model has been simulated sequentially from pillar no. 1 to 27 for the study. The vertical and yielding of the pillars (including barriers) have been obtained at different depillaring stages through simulations.

4.2.3. Simulation results for 'Case A'

The simulation results have been obtained in terms of vertical stress and yielding profile at the mid-level of the coal seam (fig. 4.5). Here, yielding refers to the failed element (which goes into residual phase) of the pillars. An unstable mining condition has been observed during the extraction of Pillar 'W.' A similar mining condition has also been observed in the field. The vertical stress profile shows the influence of goaf is up to one row of pillars, and the barrier pillars towards the goaf side yields ultimately, as seen in Fig. 4.5. After the failure of barrier pillars, the continuity overlying strata gets disturbed, leading to a reduction in the strata stiffness. It is worth noting that the range of influence zone (*R*) is higher for the stiffer strata and vice versa. Thus, after the failure of the barrier pillars, a considerable load has been distributed to the pillars near the goaf edge. The pillars nearby goaf show high vertical stress of about 12.5 MPa and yield about 6 m from the sides. The pillars away from the goaf show a symmetrical stress distribution and yield about 2 m from the sides. The far end pillars show the average vertical stress of about 8 MPa, equivalent to the tributary area load. The previously extracted pillar ('P'), the working pillar ('W'), and the next pillar ('N') have been critically analyzed using the simulation results. The average vertical stress on the focused pillars (Pillar 'P,' 'W,' and 'N') has been calculated at different stages of depillaring using program codes of $FLAC^{3D}$. The pillar 'P' and 'W' were completely yielded at the concerned depillaring stage and show the residual strength of about 0.50 MPa and 1.65 MPa, respectively. The pillar 'N' yields about 75% and shows average vertical stress of about 11.26 MPa. The numerical simulation techniques as discussed in section 3.4 has been adopted for determination of the pillar strength. The strength of the pillar, in this case, has been obtained as 12.5 MPa. The *FOS* of the next pillar ‘N’ at the concerned depillaring stage has been calculated as 1.1, as seen in Table 4.2.



Vertical stress scale (stress in Pa) | Yielding state scale

Fig. 4.5 Vertical stress and yield profile of the panel in ‘Case A’

Table 4.2 *FOS* of the next intact pillar (‘N’) in ‘Case A’

Pillar	Average vertical stress (MPa)	Pillar strength (MPa)	FOS
W	1.65	12.5	*
N	11.26	12.5	1.1

* The *FOS* of the working pillar 'W' has not been evaluated as the pillar undergoes its residual phase

4.2.4. Field observations in 'Case A'

The depillaring operation begins in the panel with the fish-bone pattern of extraction. The behavior of the strata have been monitored during the depillaring operation using various strata instruments such as auto warning tell-tale (*AWTT*), dual height tell-tale (*DHTT*), rotary tell-tale (*RTT*) for monitoring the dilation in the roof, and stress cell for assessment of the induced stress on the pillars. These instruments have been installed at strategic locations. *DTT* has been installed at all the junctions and anchored at 1.5 m and 5.0 m in the roof. *AWTT* has been installed at all main junctions and the middle of the dip galleries. The anchor of the *AWTT* has been fixed 15.0 m above the roof. It has been set at 5 mm for triggering the warning. *RTT* was installed in the middle of the level gallery and anchored 8.0 m above the roof. A stress cell has been installed at pillar no. 13 at a depth of 5.0 m in the designated snook.

It has been observed that the panel experiences adverse strata issues during the extraction of the second and third row of the pillars. Fig. 4.6 shows the interval between the *AWTT* warning and roof fall in the panel during depillaring. The average duration between *AWTT* warning and fall time has been separately calculated as 48 hrs (excluding the abnormal observation), which indicates the average stand-up time of the remnant pillars. Rotary tell-tale (*RTT*) indicates the dilation in the roof. About 73.5 % of *RTT*s have shown dilation value less than 5.0 mm, and about 16.5 % of *RTTs* have shown the roof dilation in the range of 5 mm – 10 mm. About 10 % *of RTTs* have recorded a dilation value of more than 10.0 mm. The stress cell installed at pillar no. 13 recorded the maximum 130 kPa (i.e., about 0.13 MPa) induced stress value at the time of final extraction from the pillar. It is to be noted that the induced stress recorded is very less which might be because of the already yielded pillar side.

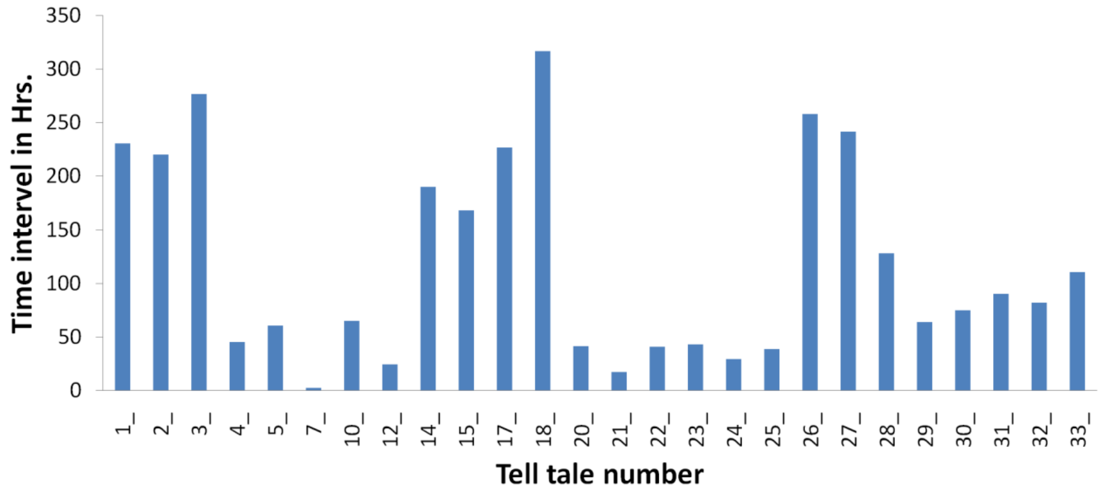


Fig. 4.6 Time interval between flashing of AWTT and roof fall in ‘Case A’

The observation of natural roof fall has been recorded in the study concerning the time, area of fall, and overhang area before and after the fall. The average area of natural fall has also been calculated as 1468 m^2. Fig. 4.7 shows the detail of falls in terms of cumulative area of goaf, progressive area of falls, and area of falls. Fig. 4.8 shows the bar chart of overhang just before and after the respective fall.

The field investigation reveals that excessive side spalling and floor heaving has been observed during the extraction of the fourth row of pillars. Continuous side spalling and roof dilation has been observed during the extraction of pillar no. 16 and 17. The influence of the goaf has been physically observed two rows of pillars ahead of the working. The mining conditions become problematic after the extraction of pillar no. 17. Partial extraction has been carried out in pillar no. 18, considering the strata issues. About two rows of pillars (pillar no. 19 – 30) have been left intact at this stage to restrict the influence of the active goaf on the workings.

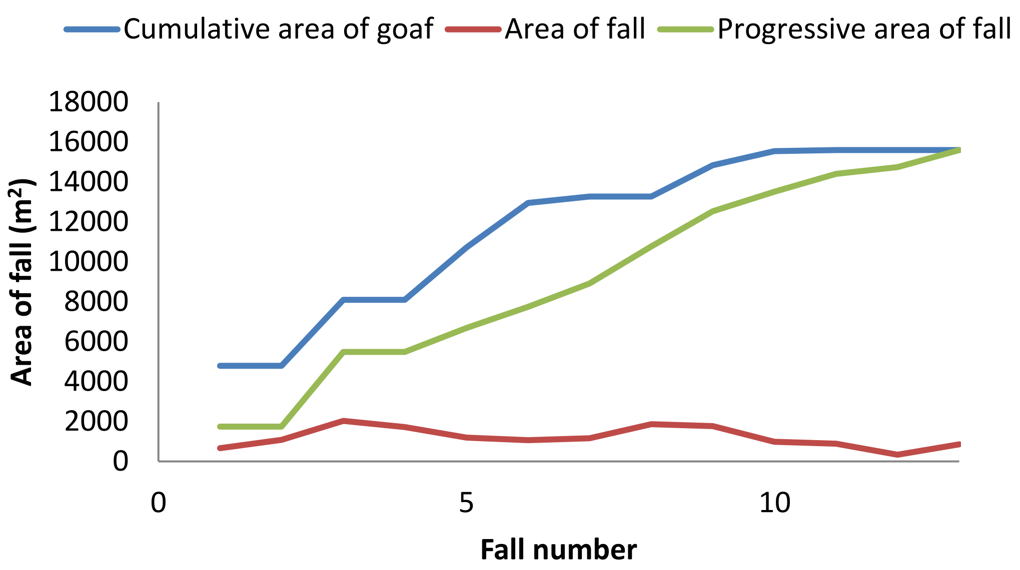


Fig. 4.7 Natural roof falls in the panel during depillaring in 'Case A'

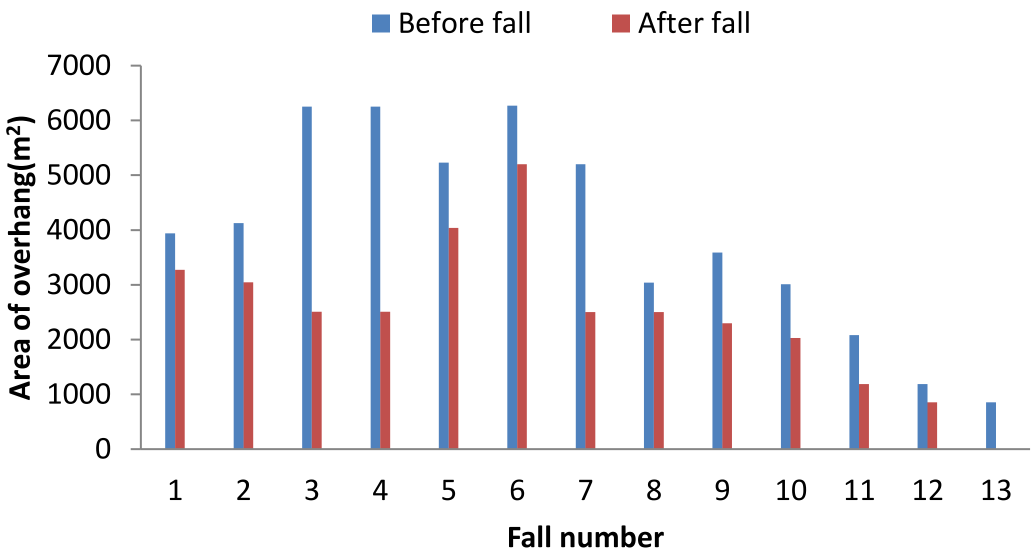


Fig. 4.8 Area of overhang before and after roof fall in 'Case A'

The simulation results also show similar mining conditions as observed in the field. Excessive side spalling and poor roof conditions observed in the field have also been depicted by the vertical stress and yield profile of the panel during depillaring. The depillaring operation has been stopped in the panel during the extraction of pillar no.

18 due to unsafe mining conditions. The model also shows similar behavior at the depillaring stage where pillar no. 19 (pillar 'W') has been extracted, as indicated through the vertical stress and yield profiles of the panel (Fig. 4.5). The *FOS* of the next intact pillar has been evaluated as 1.1, which shows further extraction of the pillar in the panel is not safe concerning the strata issues.

4.3.Case B

The panel selected in 'Case B' also belongs to the Godavari Khani coalfields, and the mine is located in Telangana's Peddapalli district under Singareni Collieries Company Limited (*SCCL*). The working coal seam (seam No. I) lies at a depth of about 190 m to 230 m within the panel. The dip of the seam is about 1 in 8.5 towards N 60° E. The average thickness of the seam is about 5.0 m. It has been observed that most of the strata consist of fine-grained sandstone. Coarse to fine-grained sandstone layers of about 3.0 thick are present up to the height of 30 m from the roof of the working seam no. I. Fine-grained sandstone layer of 16 m thick followed by 76.0 m has also been observed. The strata have been classified as moderately competent strata. Fig. 4.9 shows the borehole section present in the panel.

The coal seam has been developed in the panel along the middle section with five headings using conventional drilling and blasting techniques. The average width and height of the galleries in the panel were 4.8 m and 3.0 m. The average width of the pillars in the panel was 35 m (center to center). The panel consists of 4 x 8 pillars with four pillars along its width and ten pillars along its length (excluding barriers). The average width and length of the panel were about 175 m and 315 m, respectively. A goved out panel was present on one side of the considered panel, whereas a developed panel on the other side. Fig. 4.10 shows the layout of the panel.

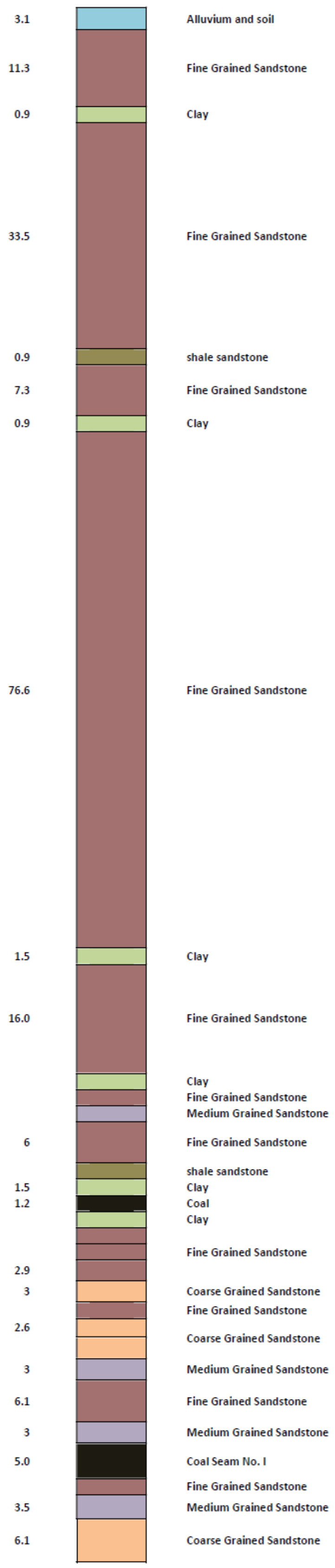


Fig. 4.9 Borehole log of the strata in 'Case B'

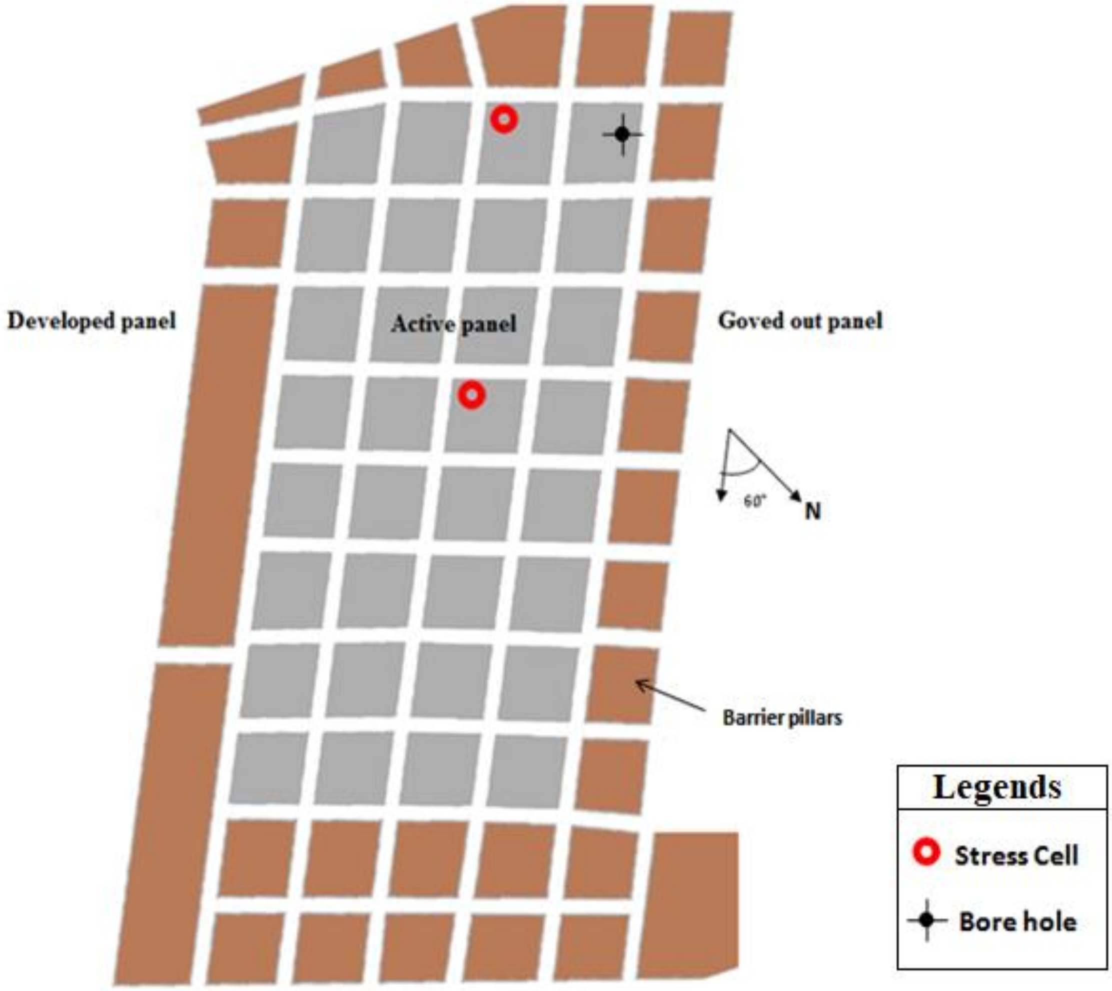


Fig. 4.10 Layout of the panel in 'Case B'

4.3.1. Depillaring operation in 'Case B'

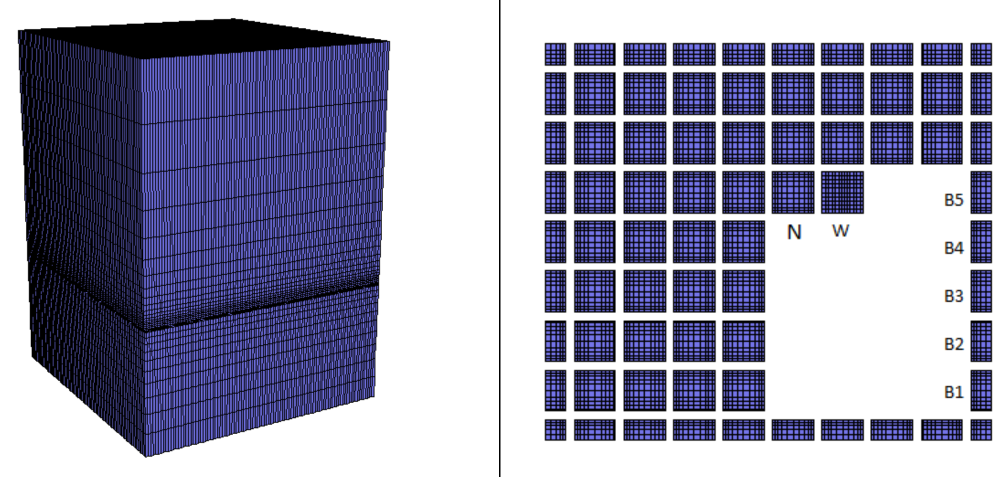
The panel adopts the mechanized depillaring operation using *CM* with split and fender patterns during the final coal extraction. The galleries in the panel have been widened to 6.0 m to facilitate the *CM* operations and heightened to 4.5 m to extract the coal present in the roof. After the widening and heightening process, the pillar size became 29 m x 29 m (corner to corner). The depillaring operation begins in the panel with a straight line of extraction. The pillars have been split into two fenders by driving a split gallery of about 6.0 m. The fenders are sliced at an angle of about 70° during final coal extraction. The first slice has been taken out by leaving an in-bye of about 5 m from the corner. Two consecutive slices of 3.5 m each have been taken out before leaving an in-between rib of about 3 m for temporary support of the strata. Afterward, three consecutive slices of about 10 m have been taken out from the fender, leaving the final snook of about 5.5 m.

4.3.2. Numerical simulation for 'Case B'

A three-dimensional numerical model has been constructed in the study for the considered panel using *FLAC^{3D}*. The model has been prepared using brick elements which comprise coal pillars, immediate strata, and main strata. A sufficiently large-sized panel has been constructed in the study, including pillars of the nearby developed panel. The model consists of an 8 x 7 array of pillars with five headings in the active panel. The pillar size in the model has been taken as 29 m x 29 m (corner to corner), whereas the width and height of the gallery as 6.0 m and 4.5 m, respectively. The roof has been constructed up to the surface (i.e., 210 m; average depth). The coal seam and roof have been joined with the 'attach' command of *FLAC^{3D}*. Fig. 4.11 shows the discretized view of the model. Fig. 4.11a shows the model's three-dimensional view, and Fig. 4.11b shows the panel's plan view at the mid-level of the pillars. The working pillar (Pillar P) was discretized into ten equal parts in x and y directions with the discretization ratio of 1. The remaining pillars have a discretization ratio of 1.2 so that the sides of the pillars become more discretized than the core. The roof and floor of the model has been discretized into 100 parts in x and y direction each, and 10 parts in z direction. The discretization ratio of the roof and floor have been taken as 2.5 and 0.5, respectively, so that the thickness of the strata close to the seam becomes highly discretized than the strata closer to the surface.

The material properties have been incorporated in the model for coal, roof, and floor, as discussed in Chapter 3. The *UCS* of the coal has been tested in the laboratory and found as 46.8 MPa. The peak cohesion value has been determined using Eq. 3.3

(Chapter 3). The strength parameters for coal used in the model have been shown in Table 4.3.



a. Three-dimensional view | b. Plan view

Fig. 4.11 Discretized view of the model in ‘Case B’

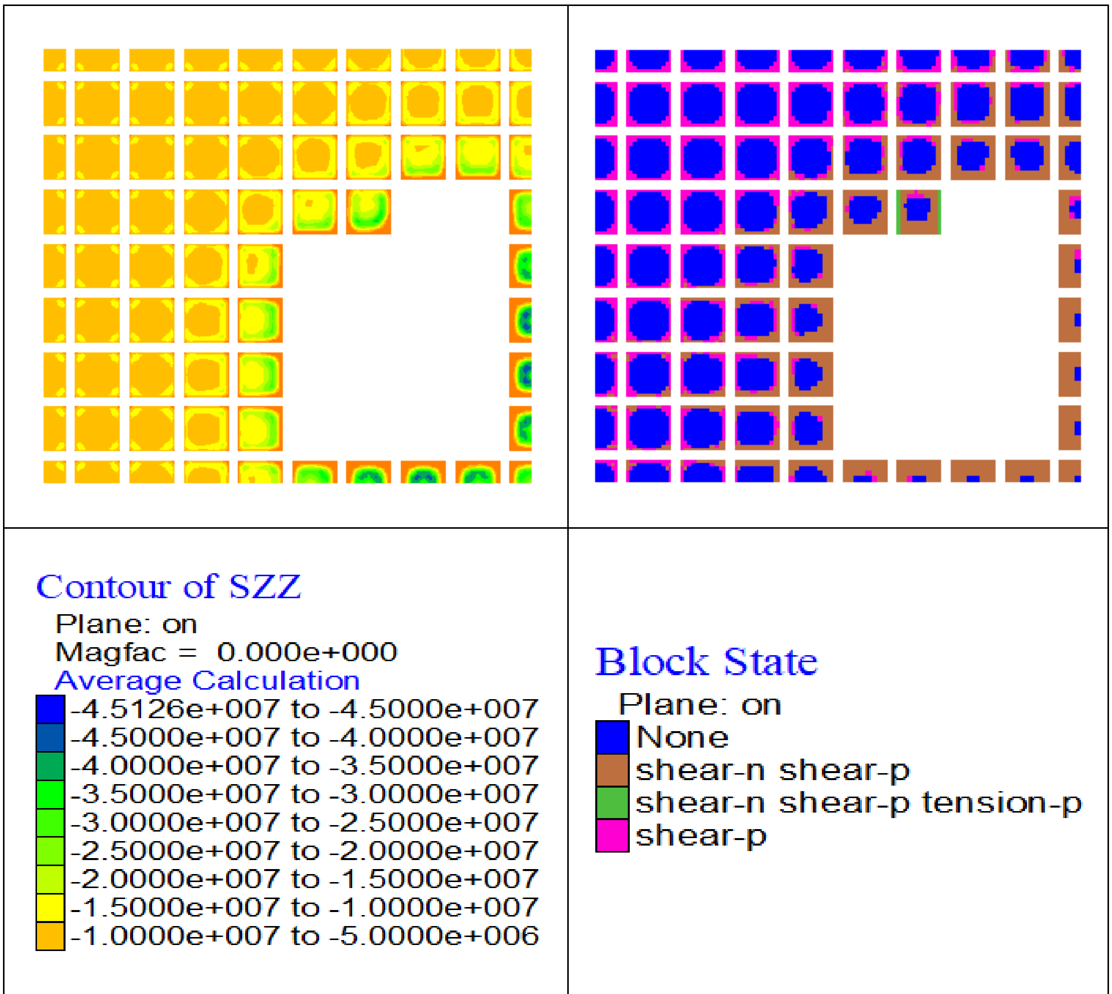
Table 4.3 Strength parameter for coal used in the model for ‘Case B’

Shear strain (m)	Cohesion (MPa)	Friction angle (°)
0	1.75	30
0.005	1.16	30
0.015	0.58	30
0.03	0.29	30
0.1	0.09	25

The base of the model has been fixed in the vertical direction, whereas all four sides in the normal direction. The top of the model is up to the surface level, hence, not fixed. The gravity component is acting normal to the coal seam in the model. The vertical stress and horizontal stress have been initialized in the model as per Eq. 4.1 and Eq. 4.3, respectively. The maximum vertical and horizontal stress at the seam level has been calculated as 5.25 MPa and 4.5 MPa, respectively. The model has been simulated sequentially with a straight line of extraction up to pillar no. 18, considering maximum stress conditions in the panel at a depillaring stage where advancement length is equivalent to the panel width.

4.3.3. Simulation results for 'Case B'

The simulation results have been obtained in terms of vertical stress and yielding profile of the panel. The status of pillars (including barriers) has been accessed at different stages of depillaring using program codes of *FLAC^{3D}*. Fig.4.12 shows the vertical stress and yielding profile of the panel at the middle level of the pillars. It has been observed from the simulation results that the pillars nearby goaf shows high stress and yield conditions at a depillaring stage before splitting/slicing of pillar no. 19. The working pillar 'W' (i.e., pillar no. 19) experienced an average vertical stress value of about 12.5 MPa, at this stage shows considerably (about 70%). The strength of the pillar has been determined separately using numerical techniques (as discussed in section 3.4) and has been obtained as 17.0 MPa. The *FOS* of the working pillar 'W' has been calculated as 1.3, as seen in Table 4.4. The working pillar 'W' seems marginally stable at this stage; thus, splitting the pillars may experience the strata issue. The immediate next pillar, 'N,' also shows considerable yielding, as seen in Fig. 4.12. The average vertical stress on the next pillar 'N' has been determined as 11.9 MPa. The barrier pillars, which are surrounded by goaf from both sides, show high yielding (about 90%). The maximum vertical stress of about 45 MPa has been observed on the barrier pillars, surrounded by the goaf from both sides (as seen by blue color in Fig. 4.12). Considerable side yielding has been observed in a couple of pillars. Therefore, the splitting of the pillars is somewhat tricky. The simulation results show difficult mining conditions at this stage (i.e., before splitting/slicing of pillar no. 19), and extraction of the working pillar (pillar no. 19) is somewhat tricky.



Vertical stress scale (stress in Pa) | Yielding state scale

Fig. 4.12 Vertical stress and yield profile of the panel in 'Case B'

Table 4.4 *FOS* of the working pillar in 'Case B'

Pillar	Average vertical stress (MPa)	Pillar strength (MPa)	FOS
W	12.5	17.0	1.3
N	11.9	17.0	1.4

4.3.4. Field observations in 'Case B'

The depillaring operation has been commenced in the panel by adopting a split and fender pattern of extraction. The behavior of the strata during depillaring has been observed in the panel using different types of strata instruments like auto-warning tell-tale (*AWTT*), rotary tell-tale (*RTT*), dual height tell-tale (*DHTT*), and vibrating wire (*VW)* stress cells. *DHTT* has been installed at all the junctions and anchored at 1.5 m and 5.0 m from the roof. *AWTT* has been installed at all the main and split junctions. The anchor of *AWTT* has been fixed 15.0 m above the roof and set at 5 mm for triggering the warning. *RTT* was installed in the middle of each original and split gallery for split and fender extraction pattern. *RTT* has been anchored 8.0 m above the roof. Two stress cells have been installed in the panel (i.e., at pillar no. 18 and pillar no. 30). The stress cells have been installed in the pillars at a depth of 5.0 m in the designated snook.

Significant strata related issue has not been faced during the extraction of pillars from pillar no. 1 to 18. The strata issues have been started during the extraction of pillar no. 19 and pillar no. 20, as the *AWTT* has shown the warning. The roof dilation has been recorded more than 5 mm before completing the respective fenders of pillar no. 19 and pillar no. 20. Therefore, fenders have not been completely extracted.

Similar strata behavior has been observed during extraction of pillar no. 23 and 24, as indicated through advanced blinking of the *AWTT*. Therefore, these pillars have also not been completely extracted. The strata issues have further exaggerated during the extraction of pillars no. from 25 to 32. Side spalling and roof dilation have been observed during the extraction of the fenders. Pillars no. 25 to 32 have also shown the side spalling during the depillaring operation. Almost all the *AWTTs* indicated the advanced blinking with roof dilation of more than 5 mm before extracting the respective fenders. The roof dilation went more than 10 mm while extracting the pillar no. 27 and 28. Roof conditions also became unstable, and roof fall had also occurred in between bolts at some locations. More than 10 mm roof dilation has been observed in the *AWTT* during the extraction of pillar no. 30 to pillar no. 32. Significant side spalling has also been observed after splitting these pillars. Therefore, these pillars have not been extracted completely. Fig. 4.13 shows the interval between the *AWTT* warning and roof fall in the panel during depillaring. It has been observed from Fig. 4.13 that the average stand-up time for the remnant pillars is about 42 hours.

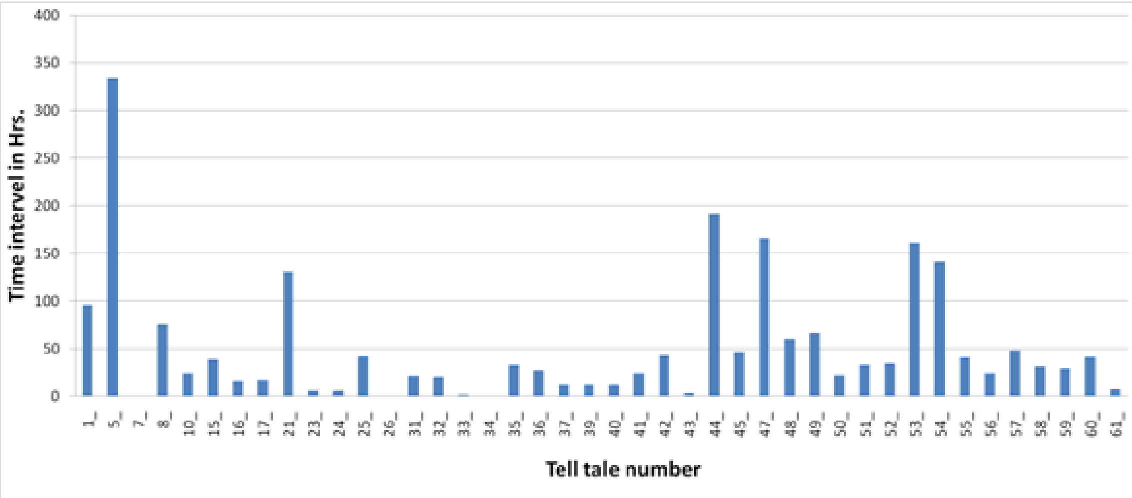


Fig. 4.13 Time interval between flashing of AWTT and roof fall in 'Case B'

The main roof fall has occurred after extraction of pillar no. 18 with an area of exposure of 13008 m^2 and advancement length of about 108 m. The time, area of fall and overhang area before and after the fall has been recorded during depillaring. Total no. of 40 natural falls had taken place in the panel. The average area of natural fall has also been calculated as 1035 m^2. Fig. 4.14 shows the detail of falls in terms of cumulative area of goaf, progressive area of falls, and area of falls. Fig. 4.15 shows the bar chart of overhang just before and after the respective fall. The average area of overhang just before the fall is about 2145 m^2.

The field investigation reveals that the extreme loading conditions have been observed during the extraction of pillar no. 19, which can also be seen from the vertical stress and yield profile of the panel (Fig. 4.12). The depillaring operation has been completed in the panel with extreme difficulties, and the pillars are partially extracted at instances where strata issues become severe. The FOS of the working pillar, in this case (i.e., 1.3), depicts the threshold limit for a smooth depillaring operation. Hence, the FOS of the working pillar should not be less than 1.3 for stable mining conditions.

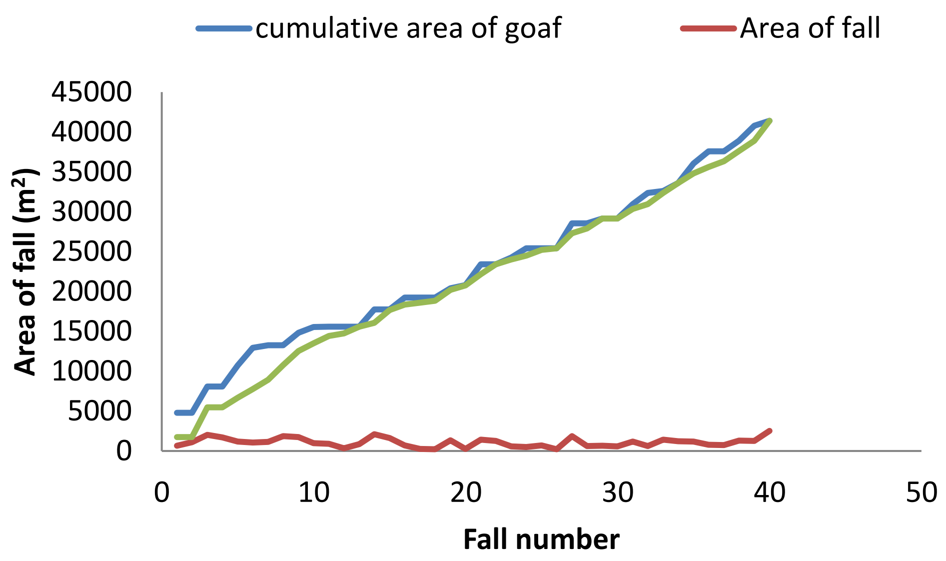


Fig. 4.14 Natural roof falls in the panel during depillaring in 'Case B'

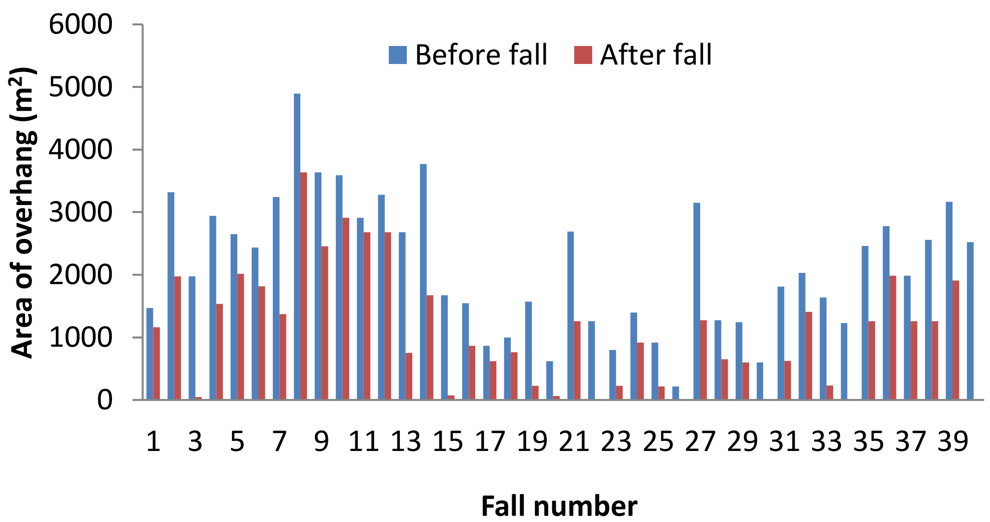


Fig. 4.15 Area of overhang before and after roof fall in 'Case B'

4.4.Case C

The bord and pillar panel of Case C belongs to the coalfields of Central India. The mine is located at the Baikuntpur area in sub-division of Kobra district, Chattisgarh, under South Eastern Coalfields Limited (*SECL*), a subsidiary of Coal India Limited (*CIL*). The coal seam in the panel was present at a depth of about 320 m – 340 m. The seam thickness varies from 4.0 m to 4.8 m. An important geological feature above the coal seam has been observed in the form of a 75 m -163 m thick and strong Dolerite sill, at a depth of about 200 m. A layer of shale of substantial thickness is present below the dolerite sill. Coarse-grained sandstone of about 5.4 was present as immediate strata. These are bound to create difficulty in the caving. Fig. 4.16 shows the borehole log of the area near the considered panel. The panel was developed with six headings using drill and blast techniques. The width of the pillars in the panel was 45 m (center to center). The width and height of the galleries in the panel were 4.8 m and 3 m, respectively. The panel consists of 70 pillars, and the size of the panel was 270 m x 675 m. The panel is surrounding by the goaf from both sides. Fig. 4.17 shows the typical layout of the panel.

4.4.1. Depillaring operation in 'Case C'

The panel adopts the mechanized depillaring operation using *CM* with a double split and fender pattern during the final coal extraction. The galleries in the panel were widened to 6.0 m to facilitate the *CM* operations and heightened to 4.5 m to extract the roof coal. After the widening and heightening process, the pillar size became 39 m x 39 m (corner to corner). The depillaring operation begins in the panel with a straight line of extraction.

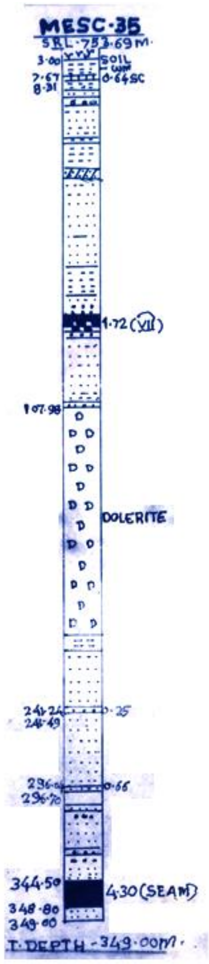


Fig. 4.16 Borehole of the strata in ‘Case C’

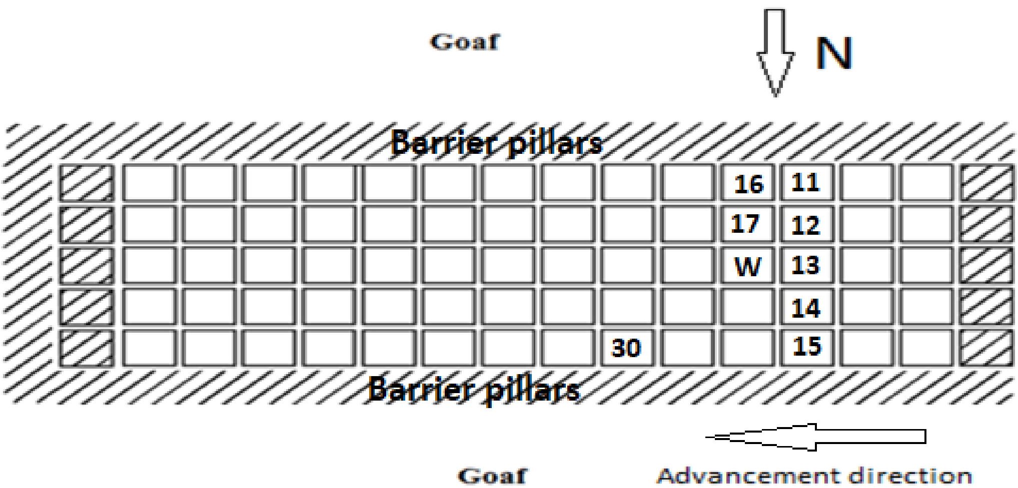


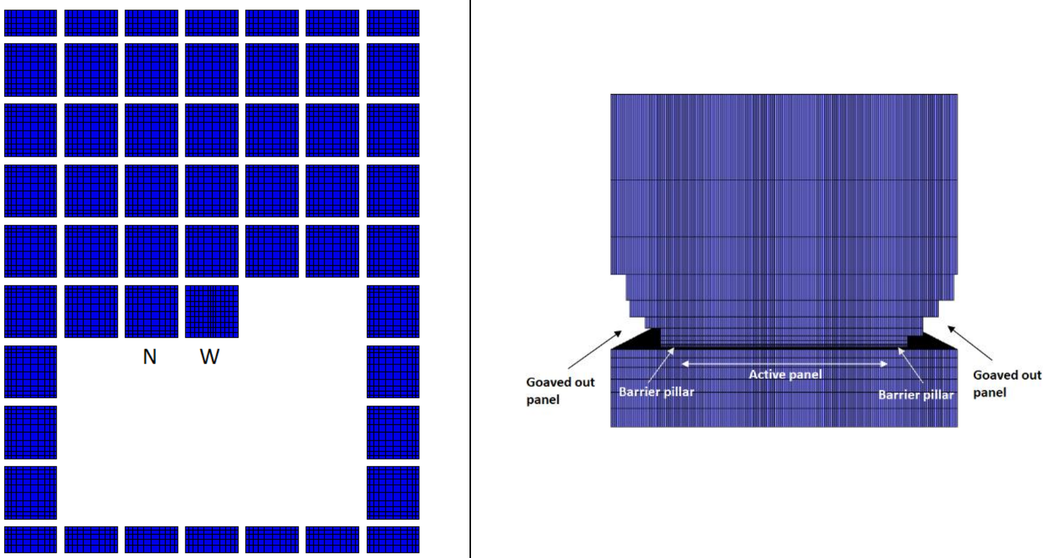
Fig. 4.17 Layout of the panel in ‘Case C’

The pillars have been split into three fenders by driving two galleries of 6.0 m each. The width of the fenders after splitting the pillar was 9 m. The fenders are sliced at an angle of about 70° during final coal extraction. The first slice has been taken out by leaving an in-bye of about 7 m from the corner. A rib of about 3 m has been left after two consecutive slices of about 3.5 m each. The resultant width of the last slice was about 9 m, leaving final snook of about 5.5 m.

4.4.2. Numerical simulation for 'Case C'

A three-dimensional numerical model has been constructed for the considered panel using *FLAC*^{3D}. The model was prepared using brick elements which comprise coal pillars, roof, and floor. The model consists of a 7 x 10 array of pillars (including the barrier pillars) with six headings. The pillar size in the model has been taken as 39 m x 39 m (corner to corner), and the gallery width and height were 6.0 m and 4.5 m, respectively. The roof in the model has been constructed up to the surface, considering the depth of cover as 330 m. The presence of a strong dolerite sill at about 100 m above the coal seam has been incorporated in the model by extending the roof from both sides of the active panel. The thickness of the floor in the model has been taken as 100 m. Fig. 4.18 shows the discretized view of the model. The discretization ratio for the pillars has been taken as 1.0, with ten equal parts in the x and y-direction and six equal parts in the z-direction. The roof and floor of the model has been discretized into 100 parts in x and y direction each, and 10 parts in z direction. The discretization ratio of the roof and floor have been taken as 2.5 and 0.5, respectively, so that the thickness of the strata close to the seam becomes highly discretized than the strata closer to the surface.

Fig. 4.18a shows the model's plan view at a depillaring stage where two and a half rows of pillars were extracted. Fig. 4.18b shows the model's sectional view at the middle of the panel, showing the extended strata incorporated in the model. The coal seam and roof have been joined with the 'attach' command of *FLAC*^{3D}.



a. Plan view | b. Sectional view

Fig. 4.18 Discretized view of the model in ‘Case C’

The coal has been considered a strain-softening material, whereas the roof and floor have been taken as elastic. The *UCS* of the coal has been tested in the laboratory and has been determined as 21 MPa. The peak cohesion value has been determined for the model using Eq. 3.3 (Chapter 3). Table 4.5 shows the strength parameters used in the model for the coal. The material properties used for coal, roof, and floor has been mentioned in Chapter 3. The base of the model has been fixed in the vertical direction, whereas all four sides in the normal direction. The top of the model is up to the surface level, hence, not fixed. The gravity component is acting normal to the coal seam in the model. The vertical stress and horizontal stress have been initialized as given in Eq. 4.1 and Eq. 4.3, respectively. The maximum vertical and horizontal stress at the seam level is calculated as 8.25 MPa and 5.7 MPa, respectively. The model has been simulated sequentially for different depillaring stages with a straight line of extraction.

Table 4.5 Strength parameters for coal used in the model for ‘Case C’

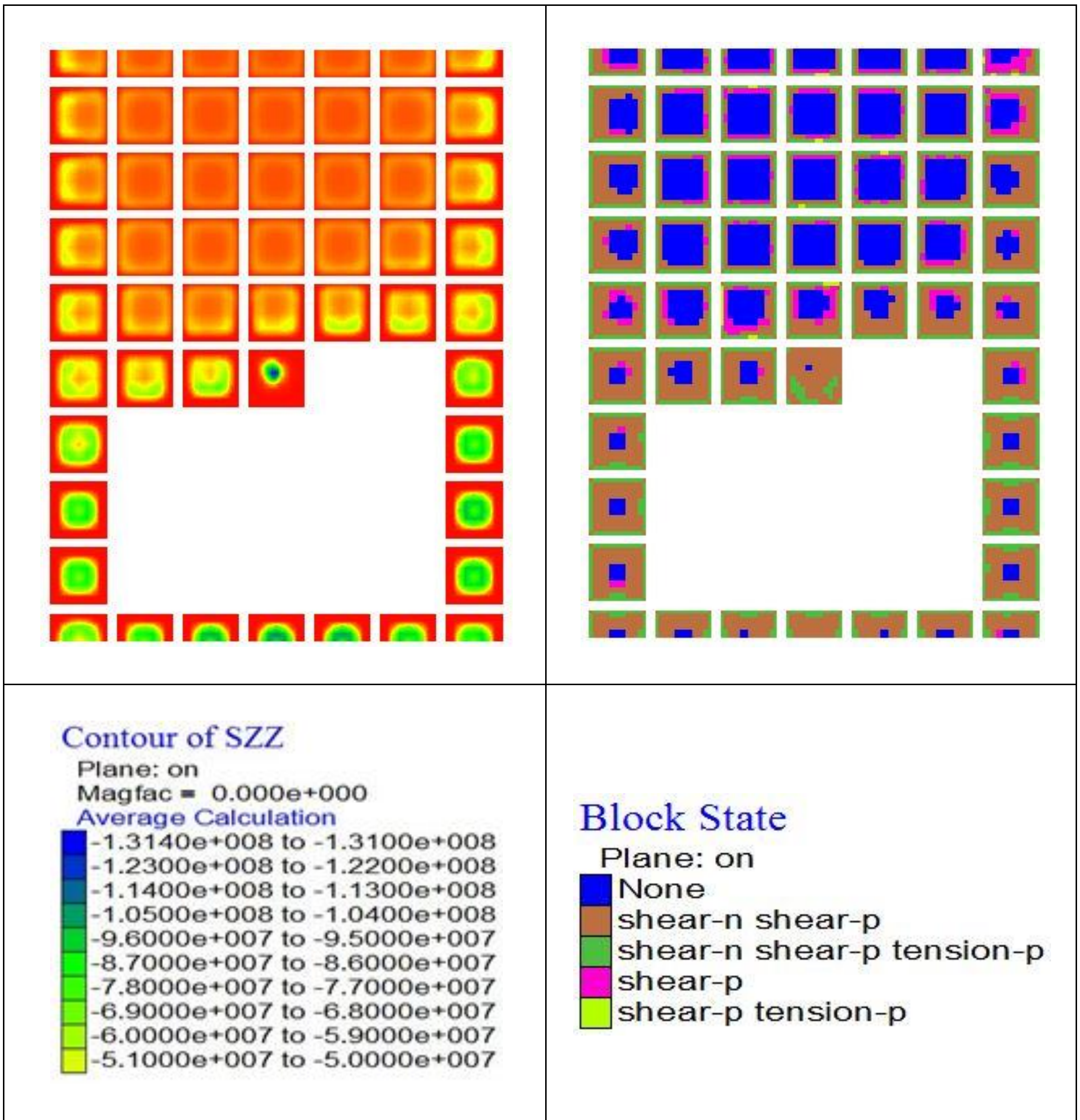
Shear strain (m)	Cohesion (MPa)	Friction angle (°)
0	0.87	30
0.005	0.58	30
0.015	0.29	30
0.03	0.14	30
0.1	0.05	25

4.4.3. Simulation results for ‘Case C’

The simulation results have been obtained in terms of the vertical stress and yield profiles of the pillars. The average vertical stress on the working pillar and barrier pillars has been calculated at different stages of depillaring using program codes of *FLAC*^{3D}. The strength of the pillar has been determined by simulating a single pillar and is 26.0 MPa (the simulation techniques has been discussed in section 3.4). An unstable mining condition has been observed before the extraction of pillar no. 18. Fig. 4.19 shows the vertical stress and yield profile of the panel at a depillaring stage before extraction of pillar no. 18. It has been observed from Fig. 4.19 that the working pillar ‘W’ has almost yielded and undergoes its residual phase. The average vertical stress on the working pillar ‘W’ has been observed as 12.3 MPa.

The simulation results show that a considerable load has been distributed to the pillars near the goaf edge, especially the working pillar ('W'). The working pillar is marginally stable at this depillaring stage; thus, splitting the pillars may experience the strata issue. The average vertical stress on the next pillar ‘N’ has been observed as 22.1 MPa. The *FOS* of the next pillar ‘N’ has been calculated as 1.2, as seen in

Table 4.6. Almost all barrier pillars show high yielding, and the barrier pillars exposed to the goaf from both sides show a yield percentage of about 85%, as seen from Fig. 4.19. The maximum vertical stress on the barrier pillars has been observed as 60 MPa. The average stress value on the barrier pillars has been observed as 23.5 MPa.



Vertical stress scale (stress in Pa)	Yielding state scale

Fig. 4.19 Vertical stress and yield profile of the panel in ‘Case C’

Table 4.6 FOS of the working pillar in 'Case C'

Pillar	Average stress on pillar (MPa)	Pillar strength (MPa)	FOS
W	12.5	26.0	*
N	22.1	26.0	1.2

'*' The *FOS* of the working pillar 'W' has not been evaluated as the pillar undergoes its residual phase

4.4.4. *Field observations in 'Case C'*

The depillaring operation has been commenced in the panel by adopting a double split and fender extraction pattern. The behavior of the strata during the depillaring operation has been monitored using various strata instruments like auto-warning tell-tale (*AWTT*), rotary tell-tale (*RTT*), dual height tell-tale (*DHTT*), and vibrating wire (*VW)* stress cells. The *AWTT* has been installed in the panel at all the split and main junctions. The *AWTT* indicates through the blinking of red light after bed separation exceeds by more than 5 mm. The *AWTT* has been considered as most reliable compared to other instruments for roof fall prediction. However, the stress cell has not found a very prominent instrument in the present geo-mining conditions as sides of the pillars have already yielded in the development stage, and thus, the load is not properly transferred on the stress cell. The *RTTs* have been installed in the middle of split galleries to monitor the immediate roof separation during the time of slicing.

The field investigation reveals that the strata issues emerge in the panel during extraction of pillar no. 11 (situated in the third row of pillars). Several stress cells have been installed in the panel to monitor the induced stress on the pillar during the depillaring stages. Fig 4.20 shows the induced stress on pillar no. 13 during the extraction of the first row of pillars. It has been observed from the stress cells that the induced stress value generally lies between 20 kg/cm^2 to 25 kg/cm^2. Advanced blinking of respective *AWTT* had been observed before complete extraction of pillar no. 14 and 15. Roof dilation of more than 30 mm had been observed in the *AWTT* and *RTTs* during the extraction of pillar no. 14 and pillar no. 15. Excessive side spalling had also been observed in the panel during the extraction of pillar no. 14 and pillar no. 15.

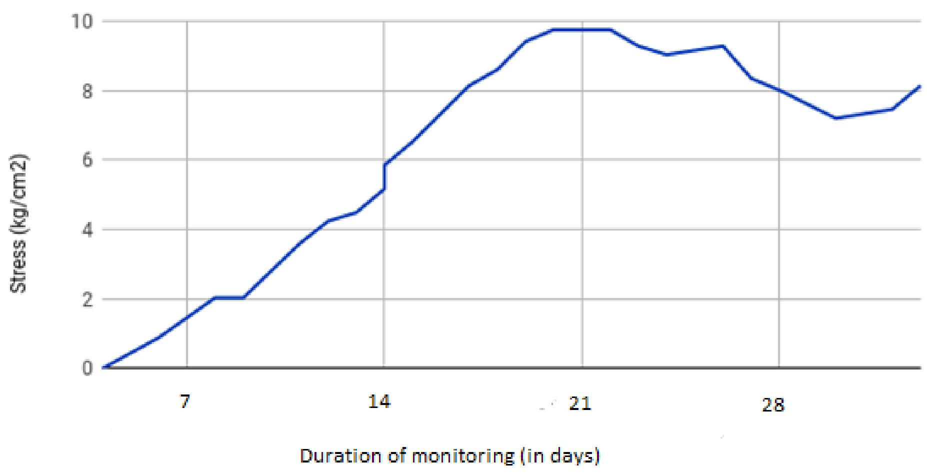


Fig. 4.20 Induced stress on a pillar no. 13 during the depillaring operation

A strong dolerite sill imposes a heavy load on the active panel and results in side spalling of the pillars. However, during the extraction of pillars in the fourth row, the induced stress values suddenly raised. The induced stress on a pillar two rows ahead (in the fifth row) builds more than 120 kg/cm^2 during the extraction of the third row of pillars in the panel. Excessive side spalling has been observed in the panel (two rows of pillars ahead of the working) due to the high value of induced stress. The depillaring operation continues in the panel with great difficulties until extraction of pillar no. 17. Afterward, the depillaring operation discontinues in the panel considering excessive side spalling of the pillars. Two rows of pillars were left intact before resuming the depillaring operation (i.e., from pillar no. 18 to 30). Similarly, after extraction of the next four rows, again, high induced stress of more than 65 kg/cm^2 has been observed four rows of pillars ahead of the goaf edge. A crack has also been observed at the roof and floor, due to which two rows of pillars have been further left in the panel.

The natural roof falls have been recorded in the study in terms of average overhang area before and after fall. The average area of natural fall has also been calculated as 2285 m^2. Fig. 4.21 shows the bar chart of overhang just before and after the respective fall. The field investigation reveals that excessive side spalling has been observed during the extraction of the fourth row of pillars. About two rows of pillars (pillar no. 18 – pillar no. 30) have been left in the panel after the extraction of pillar no. 17 to restrict the influence of the active goaf on the workings. Similar mining conditions have been observed in the model as indicated through the vertical stress and yield profile of the panel (Fig. 4.19). The working pillar 'W' (pillar no. 18) undergoes its residual phase before splitting/slicing operation and almost yields entirely, indicating an unstable mining condition.

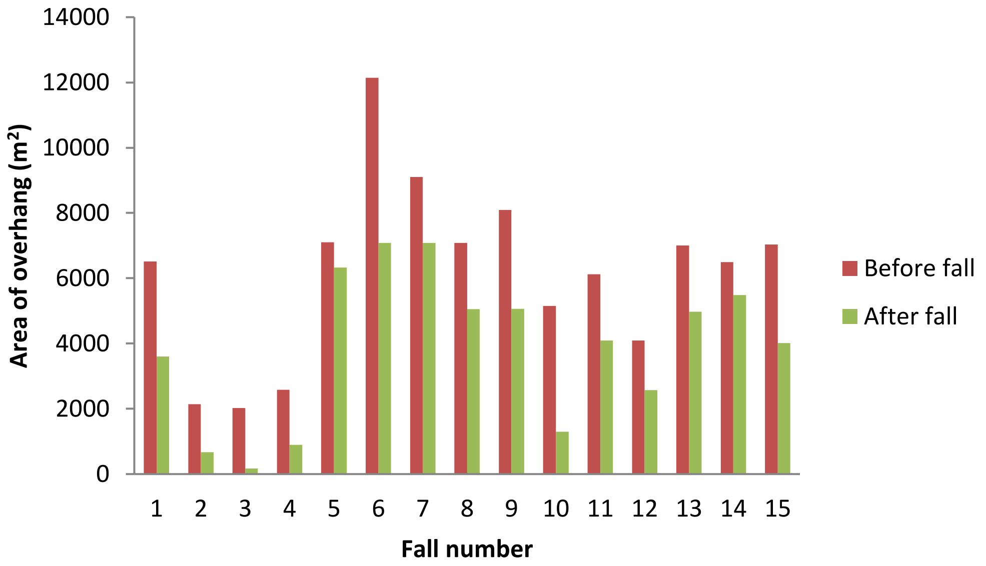


Fig. 4.21 Area of overhang before and after roof fall in ‘Case C’

4.5.Concluding remarks

Three cases of Indian coal mines adopting mechanized depillaring operations have been chosen for the study. Numerical models have been prepared for all the selected cases using *FLAC*^{3D}. The models were simulated sequentially with a straight line of extraction up to a depillaring stage at which the advancement length is equivalent to the panel width. The simulation results show an unstable mining condition in 'Case A' and 'Case C,' whereas extremely difficult mining conditions have been observed in 'Case B.' The working pillar fails and undergoes residual phase in 'Case A' and 'Case C,' whereas the working pillar 'W' is marginally stable in 'Case B.' A detailed field investigation has been carried out in the study concerning the selected panels. The field investigation reveals a similar mining condition as observed in the models. The records of *AWTT* reveal that the average stand-up time of the remnant pillars is about 45 hours. It has been analyzed from the simulation results that the *FOS* of the working pillar should not be less than 1.3 for smooth mine workings.