Chapter 3

NUMERICAL SIMULATION METHODOLOGY

3.1.General

The design of a mechanized depillaring panel plays an essential role in providing safe mining conditions. The working pillar, barrier pillars (surrounded by goaf from both sides), and remnant pillars are the critical elements of a depillaring panel. The design of pillars (including barriers) governs the global stability, whereas the design of the remnant pillars (ribs/snooks) depicts the local stability of a depillaring panel. The design of these key elements depicts the success of the mechanized depillaring panel and needs to be designed wisely. Numerical techniques have been used in the study to design the panel for mechanized depillaring. The methodology adopted to design the mechanized depillaring panel has been discussed in this chapter. Further, the coal mass strength parameters have been accessed in the study for the numerical simulations.

3.2. Analyses tool

Numerical simulation techniques are widely used nowadays in geotechnical engineering to deal with complex geo-mining conditions. It is a tool to simulate the structures holistically by considering various geo-mining complexities and provides an ideal platform for the parametric study (Mandal et al., 2018). The high computational speed of the numerical techniques enables the simulation of large structures in a reasonable time. Many researchers have adopted numerical techniques for the stability assessment of underground coal mine structures (Jaiswal et al., 2004;

Jaiswal and Shrivastva, 2009; Singh et al., 2011; Singh et al., 2016; Chawla et al., 2017; Jena et al., 2019).

Continuum analysis software, *FLAC*^{3D} (Fast Lagrangian Analysis of Continua in three dimensions) (Itasca, 2000), based on finite difference method, has been used in the study for designing the mechanized depillaring panel. *FLAC*^{3D} is a widely used numerical software for geotechnical analyses of soil, rock, groundwater, constructs, and ground support. Such analyses include engineering design, factor of safety prediction, research and testing, and back-analysis of failure. The software utilizes an explicit finite volume formulation that captures the complex behaviors of models that consist of several stages, show large displacements and strains, exhibit non-linear material behavior, or are unstable (including cases of yield/failure over large areas, or total collapse). It is based on the finite difference numerical method with Lagrangian calculation by solving ordinary differential equations. It consists in approximating the differential operator by replacing the derivatives in the equation using differential quotients. The software simulates the structure in time steps.

3.3.Design approach

Intact pillars and remnant pillars are the critical elements of a mechanized depillaring panel. The depillaring operation results in caving of the overlying strata to release the strata pressure. The caving of the strata mainly occurs in two phases, i.e., local fall and main fall. The failure of immediate strata is generally termed as local fall, whereas the failure of multiple strata beds until complete filling of the goaf is the main roof fall. The design of the pillars (including barriers) mainly governs global stability, whereas the local stability is mainly governed by the design of the remnant pillars. The stability of the pillars and remnants depicts the success of the mechanized depillaring operation.

An attempt has been made in the study to design the mechanized depillaring panel using numerical techniques. A three-dimensional numerical model of the panel has been prepared using *FLAC*^{3D}. The discretization of the model plays an important role in governing the accuracy of the model. A highly discretized model generally requires a large computation time. A large domain area of *B & P* system has been constructed in the study. Fine discretization of the whole model will take huge computational time. Thus, the pillar has been discretized in a graded mesh. The sides of the pillar have been finely discretized than the core to maintain the accuracy. The pillars are discretized into ten 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 direction and 90 parts in y direction each, maintaining a minimum discretization ratio of 1.5 (between adjacent beds) for the attach command. The width of the elements in the roof and floor lies in the range of 2 m – 4 m. The roof and floor have been discretized in the z direction such that the portion of the roof and floor strata nearby coal becomes closely discretized than the far end portion. The aim of the study is to propose the guideline for *CM* depillaring panel. Worse scenario has been considered in which the depillaring advances to a length equivalent to the panel width. The model has been simulated sequentially up to this stage considering competent strata. Thus, goaf has not been incorporated in the model. The local falls have been simulated by removing the immediate strata up to the last overhang area vis-à-vis advancement in the depillaring operation. The vertical stress (σ_v) has been initialized in the model using Eq. 2.12, whereas the horizontal stress (σ_h) has been initialized in the model using Eq. 2.14.

The numerical model has been validated with three field cases of bord and pillar panels adopting *CM* technology during the depillaring operation (Chapter 4). The design parameters have been set for the study, and numerical models were prepared and simulated for each combination of the selected parameters (Chapter 5). The stable cases of the mechanized depillaring panel have been identified by considering the design criteria (Chapter 6). Based on the analysis, guidelines have been provided to design the bord and pillar panel for mechanized depillaring. The steps involved in designing the panel for mechanized depillaring are:

Step 1: Calibration of material properties

Step 2: Validation of the numerical model

Step 3: Deciding the design parameters

Step 4: Numerical simulation of different combinations of the selected parameters

Step 5: Analysis of the simulation results

Step 6: Developing guidelines to design the mechanized depillaring panel

The study has been commenced in two phases, i.e., a) Designing of the panel and b) Designing of the remnant pillars. The design approach adopted for designing the panel and remnant pillars have been discussed in the subsequent sub-sections.

3.3.1. Panel design approach

The pillars (including barrier) are the critical elements of a depillaring panel that observes induced stress during the depillaring operation. The pillars near the goaf edge face the maximum induced stress before the main roof fall. As the goaf advances, induced stress increases till (1) the failure of the overlying strata reaches up to the surface or (2) advancement nearly equivalent to the panel width. Based on the discussion with officials of various coal mines, induced stresses reach its maximum value at a depillaring stage where advancement length is equivalent to the panel width, specifically for a competent stratum. At this stage, the value of induced stresses will be maximum on the intact pillars. The working pillar and barrier pillars (surrounded by goaf from both sides) must be stable during the depillaring operation for safe mine workings. The study has been carried out considering a competent roof stratum. The stability of these pillars at a critical depillaring stage has been assessed in the study using numerical simulation techniques. The average vertical stress on the working and barrier pillars has been obtained through the *FISH* function of $FLAC^{3D}$. The strength of the pillar has also been determined numerically by simulating a single pillar, using the technique provided in section 3.4. The *FOS* of the working and barrier pillars have been calculated for different geo-mining conditions.

Fig. 3.1 shows a typical layout of the depillaring panel at a critical depillaring stage and the focused pillars (working and barrier pillars). The working pillar is considered the one which is about to be depillared. The *FOS* approach has been used in the study to determine the stability of the focused pillars (i.e., working and barrier pillars). The panel's optimum design is considered the one in which the *FOS* of the working and barrier pillar is more than 1.3 (preferably more than 1.5) and 1.0, respectively.

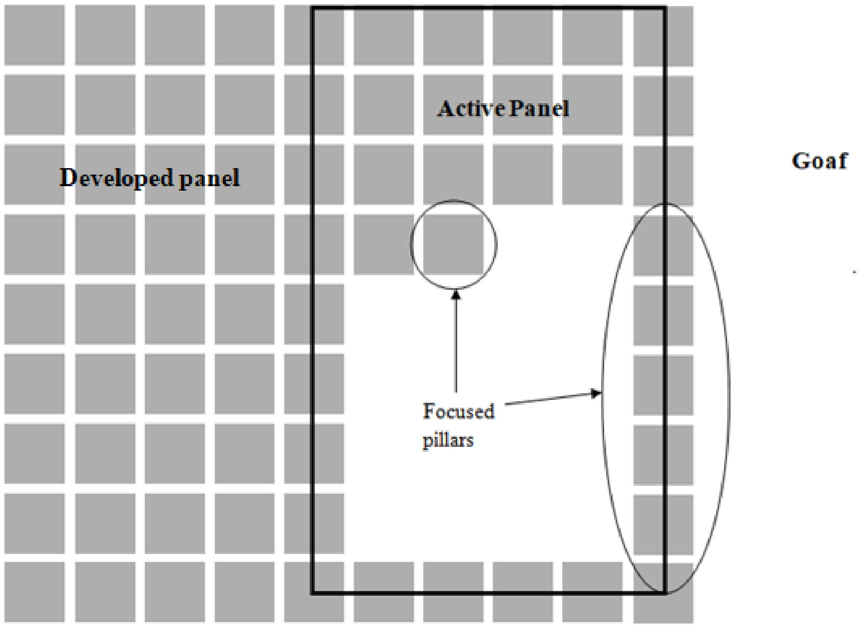


Fig. 3.1 Typical layout of the panel showing critical depillaring stage and focused pillars

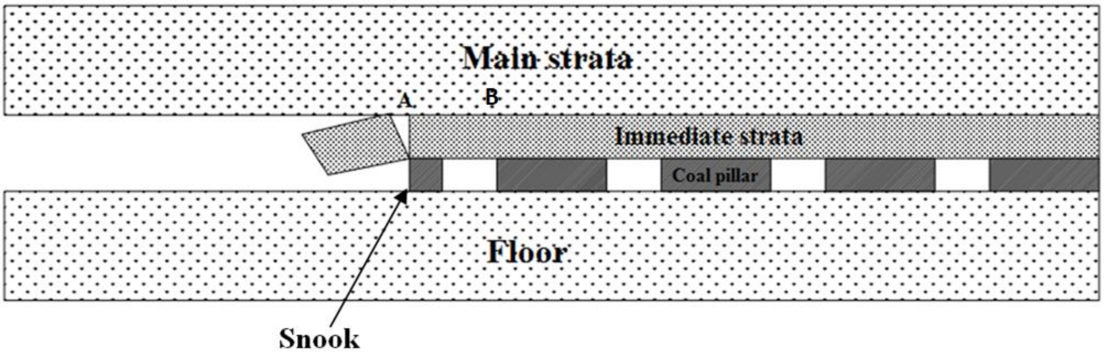
3.3.2. Remnant pillar design approach

The roof in a coal mine is generally made of stratified rock layers having a variable thickness and mineralogical composition. A wide variation in the overlying strata's behavior has been observed during the mining operation due to the difference in the physicomechanical properties. The immediate strata bed tends to separate from the main strata during the depillaring operation and behaves like a beam. Compressive and tensile stress has been generated at the floor and roof of the immediate strata, respectively, during this stage (Chawla S., et al, 2017). The advancement in depillaring operation increases the stress values in the immediate strata, and once the stress values reach their threshold limits, roof failure occurs. After the first roof fall, the immediate strata act as a cantilever and impose their weight on the remnant pillars (ribs/snook). Snook is the last natural support against goaf, and its size is generally kept larger than other ribs concerning safety. The immediate strata's failure process is explained through a schematic diagram, as shown in Fig. 3.2. Two situations generally arise during the mechanized depillaring operation depending upon the size of the snook:

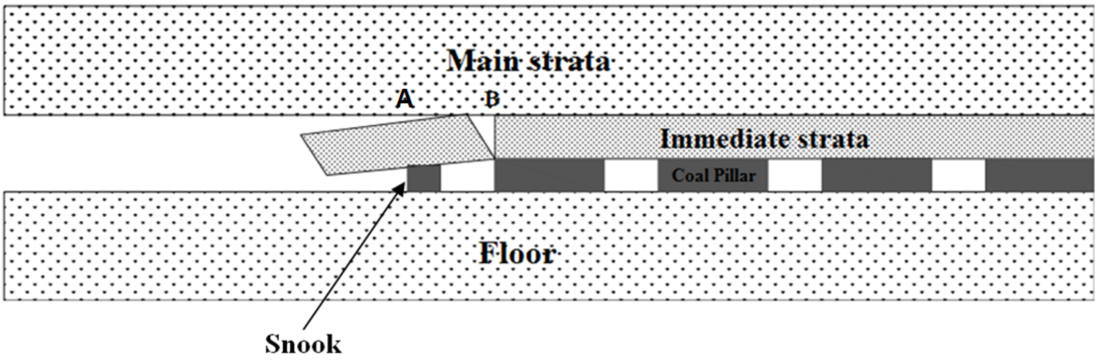
i) If the size of the snook is sufficiently large, then a considerable reaction will be provided to the immediate strata. Maximum tensile stress will be generated at the roof of the immediate strata near point 'A' as shown in Fig. 3.2a. The high tensile stress leads to the development of a failure crack. The initiation and propagation of the failure crack arise from point 'A.' The immediate strata fail ahead of the snook in this situation.

ii) If the size of the snook is small, then it will not provide a considerable reaction to the immediate strata. Maximum tensile stress will be generated at the roof of the immediate strata near point 'B,' as shown in Fig. 3.2b. In this situation, the initiation and propagation of the failure crack arise from point 'B,' failing the immediate strata behind the snook.

The former condition allows the strata's caving beyond the snook, i.e., in the goaf side, providing sufficient time to evacuate men and machinery. In contrast, the latter condition causes the strata's cave behind the snook, i.e., towards the solid pillar, resulting in overriding situations.



a. Maximum tensile stress at location 'A'



b. Maximum tensile stress at location 'B'

Fig.3.2 Failure mechanism of the immediate strata

A variety of extraction patterns have been adopted during mechanized depillaring operations, which results in different shapes of remnant pillars (ribs/snooks). The remnant pillars are the critical element of a depillaring panel, as the design of the remnant pillars mainly governs the local stability in the working area. The role of the remnant pillars is to withstand the immediate strata's load until the withdrawal of men and machines to a safe distance. The load of the immediate strata results in yielding of the remnant pillars (ribs/snooks) during final coal extraction, and the remnant pillars exhibit residual strength. If the residual strength of the remnant pillars (ribs/snooks) is not sufficient to hold the immediate strata, there may be a chance of overriding. On the other hand, if the remnant pillars (ribs/snook) residual strength is higher than the desired value, it delays the strata's caving. Thus, the remnant pillars (ribs/snooks) optimum size is required to hold the immediate strata without inhibiting caving. In the study, an attempt has been made to design the remnant pillars (ribs/snooks) for the mechanized depillaring panel using numerical techniques. The optimum remnant pillars (ribs/snooks) design is considered to be the one that holds the immediate strata until the extraction of the next pillar, maintaining a safe distance between the goaf edge and the working face.

The term *'Strength Factor (SF')* has been coined in the study to depict the stability of the remnant pillars. *SF* is the ratio of the weight of the overhang and the residual strength of the remnant pillars (Eq. 3.1).

$$SF = \frac{Residual\ strength\ of\ the\ remnant}{Weight\ of\ the\ overhang} \tag{3.1}$$

The optimum remnant pillar design is considered to be the one in which the *SF* of the previously extracted pillar/remnant (‘P’) is less than 1.0, and the *SF* of working pillar/remnant ('W') is more than 1.0, at a depillaring stage where the last slice has been taken out from the working pillar (‘W’). Fig. 3.3 shows the typical layout of a depillaring panel, including remnant pillars.

The *SF* of the remnant pillars has been calculated by determining the weight of the overhang and the residual strength of the remnant pillars. The overhang formed during the final extraction of coal is mainly composed of the immediate strata. In general, the mine management keeps the record of the roof falls. The area of the local fall (failure of the immediate strata) depicts the overhang area, which needs to be supported through remnant pillars (ribs/snooks), and the height of the probable overhang can be determined using the borehole log of the panel. Thus, the immediate strata's (overhang) load can be easily estimated by determining the overhang's volume. The weight of the overhang can be estimated using Eq. 3.2. In the present study, the volume of the immediate strata (overhang) has been considered by taking the overhang's area equivalent to the pillar size and its thickness as 4.0 m considering the field investigations.

$$Weight\ of\ overhang = (Volume\ of\ the\ overhang)\ X\ (\text{density}) \tag{3.2}$$

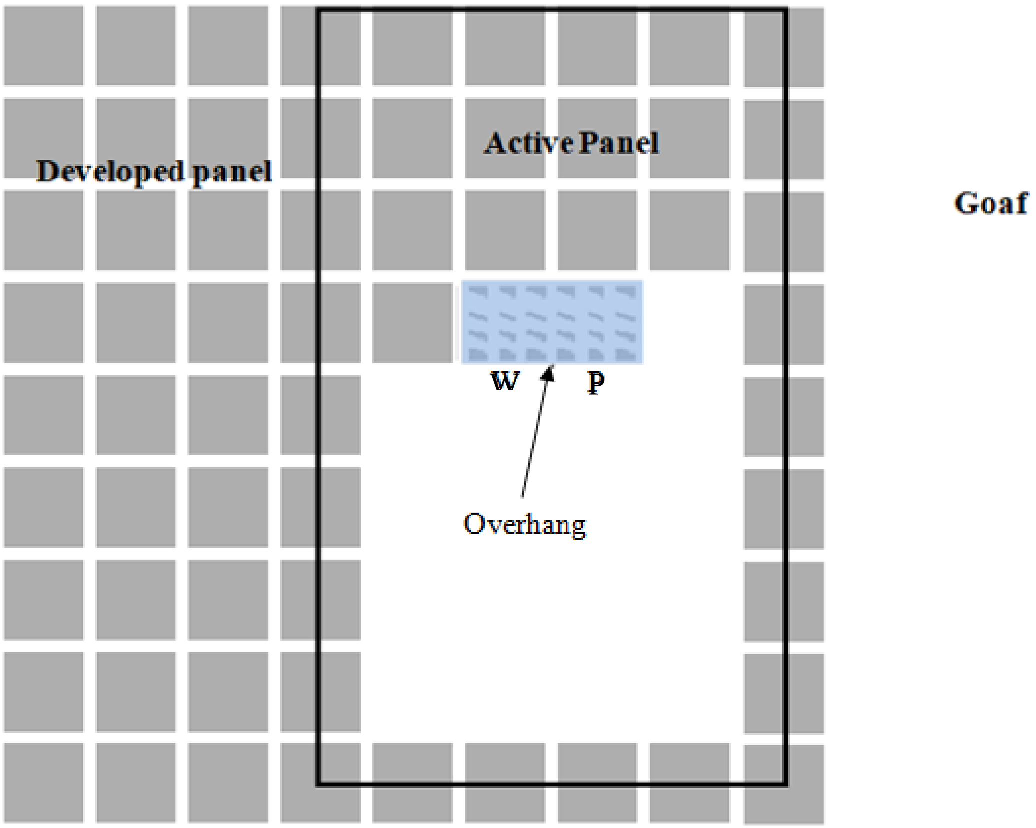


Fig. 3.3 Typical layout of the panel showing focused remnant pillars

Numerical models have been prepared in the study for different combinations of pillar widths and extraction schemes. Numerical techniques were used to determine the residual strength of the remnant pillars (ribs/snooks). The optimum remnant pillar design is considered to be the one that satisfies the design criteria, which states that the *SF* of pillar/remnant ‘P’ < 1.0 and *SF* of pillar/remnant ‘W’ > 1.0, at a depillaring stage where the last slice has been taken out from the working pillar (‘W’). The optimum remnant pillar design has been obtained for different pillar sizes by varying the size of the final snook. Fig. 3.4 shows the flow chart showing the designing sequence adopted for obtaining an optimum remnant pillar design.

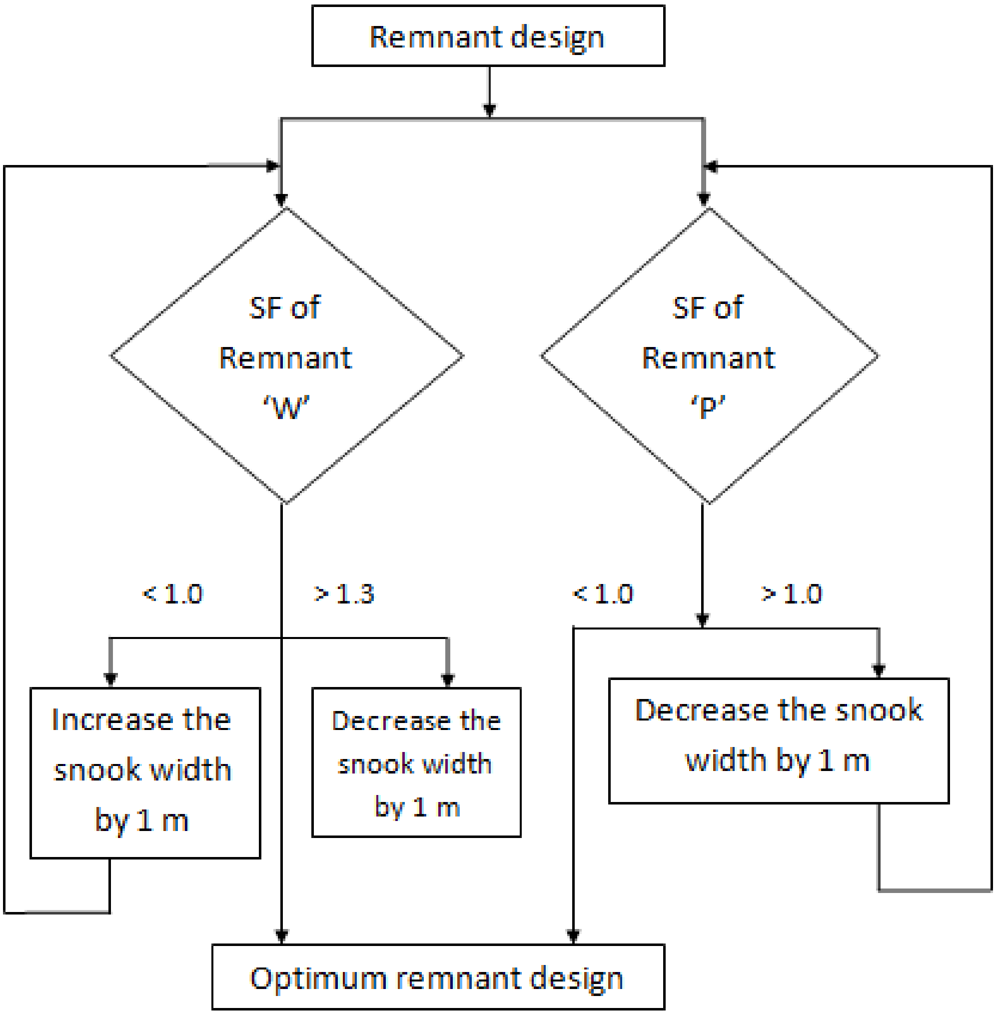


Fig.3.4 Flow chart showing designing sequence adopted for optimum remnant pillar design

3.4.Coal mass strength parameters

The calibration of the material properties is the essential requirement of the numerical model, as incorrect material properties may replicate false results. The back analysis techniques have been used in the study to derive the material properties for the model. It is practically impossible to determine the constitutive behavior of coal mass in the laboratory. Thus, generalized strain-softening constitutive coal-mass behavior for Indian coalfields was determined using the back analysis technique. Failed and stable coal pillars from Indian coal mines have been considered in this study to calibrate the material properties (Sheorey 1992). The details of the failed and stable cases of Indian coal mines have been provided in Appendix - A. Researchers generally consider coal as either Hoek – Brown material (Medhurst, 1998; Jaiswal and Shrivastva, 2009) or Mohr-Coulomb material (Murali et al., 2001; Kumar et al., 2017). In the present analysis, coal mass has been considered as Mohr-Coulomb strain-softening material.

Three-dimensional models of coal pillars were constructed for all the stable and failed cases. The model comprises a coal pillar, roof, and floor. Fig. 3.5 shows the discretized view of the model for the coal pillar. The coal's dilation angle and tensile strength have been considered as 0.0° and 0.6 MPa, respectively. The Young's modulus and Poisson's ratio for coal have been taken as 2 GPa and 0.25, respectively. Table 3.1 shows the material properties used in the model for coal. Table 3.1(a) shows the physicomechanical properties, and Table 3.1(b) shows the softening parameters used in the model for coal.

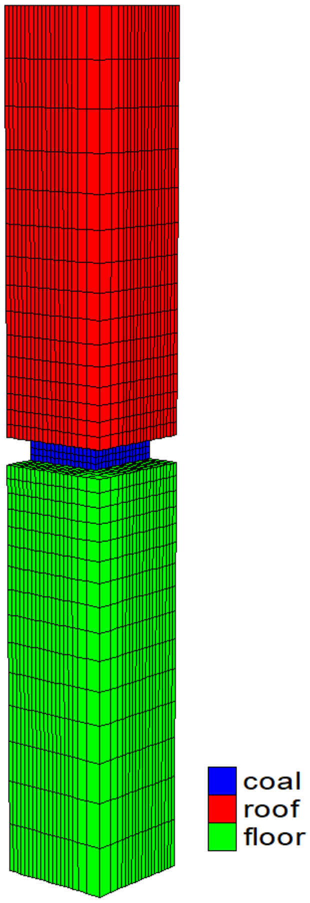


Fig. 3.5 Typical discretized view of the model for the coal pillar

Table 3.1 Material properties used in the model for coal

a) Physico - mechanical properties

Material	**Material type**	**Density (kg/m^3)**	**Young's modulus (GPa)**	**Poisson's ratio**	**Dilation angle (°)**	**Tensile strength (MPa)**
Coal	Strain - softening	1300	2	0.25	0	0.6

b) Softening parameters

Shear strain (m)	**Cohesion (MPa)**	**Friction angle (°)**
0	c	30°
0.005	c/1.5	30°
0.015	c/3.0	30°
0.03	c/6.0	30°
0.1	c/18.0	25°

‘c’ is the peak cohesion (Eq. 3.3)

Mohr-Coulomb strength parameters (c and ϕ) are adjusted in the model by the hit and trial method such that the failed cases show a *FOS* less than one, whereas stable cases show a *FOS* of more than one. The peak value of the internal friction angle (ϕ) has been considered as 30°. It has been observed during the hit and trial practice that the friction angle has little influence over the pillar strength as compared to the cohesion. A strong relationship between peak cohesion (c) value and uniaxial compressive strength (*UCS*) of the coal-mass (Eq. 3.3) has been observed after calibration as given below:

$$c = (0.034)UCS + 0.153\ (MPa) \qquad (3.3)$$

where *c* is cohesion and *UCS* is uniaxial compressive strength.

The value of cohesion and internal frictional angle w.r.t. plastic shear strain is shown in Table 3.1(b). Roof and floor have been considered elastic with Young's modulus and Poisson's ratio of 5 GPa and 0.2, respectively. Table 3.2 shows the material properties used in the model for roof and floor. The bottom of the model has been fixed in the vertical direction, whereas the sides in the normal direction. The top of the model is allowed to deform in the downward direction at a constant velocity. The analysis satisfied about 50% and 92% of failed and stable cases. The *FOS* of the failed and stable cases obtained through numerical simulations have been shown in Appendix - A. Fig. 3.6 shows the graphical representation of all the cases in terms of stress on the pillars vis-à-vis the strength of coal pillars.

Table 3.2 Material properties used in the model for roof and floor

Material	**Material type**	**Density (kg/m^3)**	**Young's modulus (GPa)**	**Poisson's ratio**
Roof	Elastic	2500	5	0.2
Floor	Elastic	2500	5	0.2

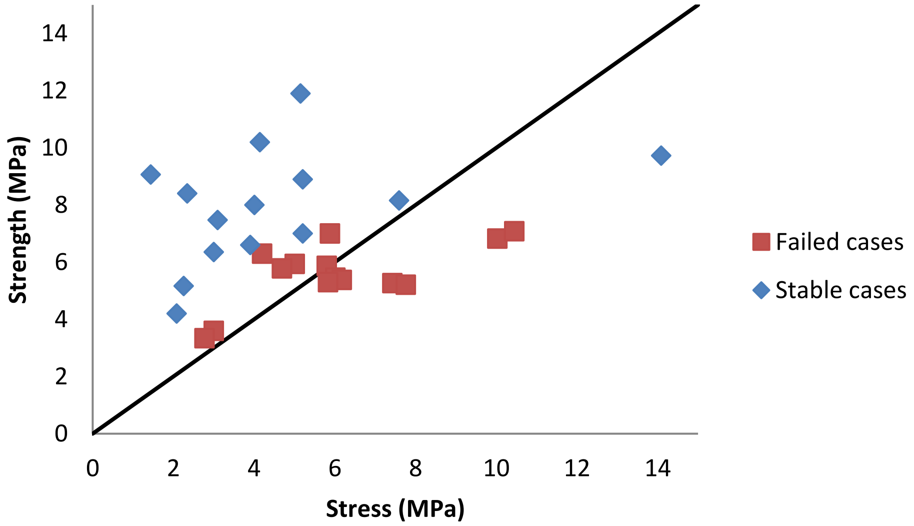


Fig. 3.6 Numerical pillars strength and stress

3.5.Concluding remarks

The methodology adopted to design the panel for mechanized depillaring has been discussed in this chapter. Numerical techniques have been used to determine the stability of the intact pillars and remnant pillars in the depillaring panel. A critical depillaring stage has been chosen for the study such that the advancement length is equivalent to the panel width. The *FOS* approach has been adopted in the study to design the pillars (including barriers), and *SF* has been used to design the remnant pillars (ribs/snooks). The optimum panel design is considered the one in which the *FOS* of the working pillar is more than 1.3 (preferably more than 1.5), and the *FOS* of the barrier pillars is more than 1.0 at the critical depillaring stage. The optimum design of the remnant pillars (ribs/snooks) is considered to be the one where the *SF* of the working pillar/remnant (‘W’) is more than 1.0 and the *SF* of the previously extracted pillar/remnant ('P') is less than 1.0, at a depillaring stage where the last slice has been taken out from the working pillar ('W'). The coal mass strength parameters have been determined using back analysis technique. Failed and stable coal pillar cases from Indian coal mines have been considered in the study to calibrate the material properties. A linear relationship has been observed between peak cohesion (*c*) value and uniaxial compressive strength (*UCS*) of the coal mass during material calibration.