DESIGN OF CHAIN PILLARS FOR DEEP LONGWALL WORKINGS IN INDIAN GEO-MINING CONDITIONS

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By

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Chapter 10

10. Discussion and Conclusion

10.1 Discussion

General

This dissertation aimed to evaluate the failure mechanism of chain pillars and establish an approach for their rational design for deep longwall workings in Indian geo-mining conditions. The literature review covered the general understanding of stress redistribution and damage of overlying roof strata that lead to the different intensity and quantum of load transfer on the chain pillars in different geo-mining conditions. It also highlighted the design requirement of such structures based on theoretical understanding and field experiences. The state of the art of chain pillar design, their strengths and limitations were also highlighted in the context of deep longwall workings in Indian conditions. The study showed that although a significant knowledge base is available for characterising the post-failure behaviour and strength of the pillars, further work was needed to estimate the overall behaviour for the optimal design of chain pillars.

The mechanical behaviour of the pillar was closely associated with its w/h ratio and confinement provided by contact surfaces, followed by post-failure softening and dilatancy of the material. Abutment angle was a critical parameter to be carefully assessed with due consideration of the depth of cover, length of the face, and mechanical properties of the overlying strata for a field representative understanding of the behaviour of the chain pillars in a given set of conditions. An appropriate understanding of the behaviour of the Caved, Fractured, and Continuous Deformation zones in the overlying strata were also crucial for appropriately considering different loading in subcritical and supercritical workings. The design criteria for deciding the size of the chain pillar were found to be highly sensitive to the strength estimation method. Hence, a thorough evaluation of a specific criterion over a field representative database of stable and failed pillars was required to develop reasonable confidence in its applicability. In the absence of any scientific approach for the design of chain pillars, particularly for deep working, the prevailing practice is wholly based on site-specific field experiences. With the further increasing depth of mining in the coming time, it becomes essential to develop a scientifically valid approach to meet the design requirements of the mine not only to ensure the safety of the workings but also for conservation of the minerals and an informed decision making.

In consideration of the above, the research methodology for the design of the chain pillar in this dissertation considered a field representative behaviour of the Caved, Fractured and Continuous Deformation zones, a standardised method for estimating their constitutive behaviour parameters and estimation of the abutment angle for various geo-mining conditions, analysis of the peak and post-peak strengths of the different pillars, the design criterion for selection of the optimum size chain pillars and the validation of findings. The entire exercise comprised a series of numerical modelling studies to meet the specific requirements.

Simulation of the Complete Stress-Strain Behaviour

The post-failure strength parameters for different coal seams were estimated by using Model III, simulating the observed behaviour during the servo-controlled uniaxial tests in the laboratory for w/h ratio ranging from 0.5-13.5 for six coal seams pertaining to three different coalfields in India. The study considered 126 calibrated models to develop a set of empirical relations for selecting post-failure strength parameters to simulate the strain-softening behaviour of the coal specimen for different w/h ratios. A reasonable estimate of the dilatancy properties and the properties of interfaces at the contact surfaces were also worked out for improved simulation of the post-failure behaviour.

The modelling study for the Singhpur middle coal seam indicated that the volumetric strain reversed to the opposite trend, with the axial strain for the w/h ratio exceeding 4.5. The stress versus strain profile confirmed the transition of post-failure behaviour from strain-softening to ductile. The uniaxial compression test for this sample showed considerable dilation till w/h of 4.5. For the w/h ratio exceeding 7.7, the specimen showed strain-hardening behaviour with accelerated development of positive volumetric strain and an insignificant dilation during the axial loading. The plots of failure state and slippage of the interface at the contact surfaces established that the core of the specimens could hold their stability even after the failure of the ribs and slippage of the interface at these locations. However, the extent of slippage, as well as the failure, reduced with the increasing w/h ratio. Although the specimen having a w/h ratio of 4.5 showed complete failure during its uniaxial compression, the interface could hold its original position in the centre, helping the specimen retain its residual strength after failure. The plot of differential stress and volumetric strain also confirmed the closure of dilation as indicated by the positive volumetric strain in such specimens.

The validation of the modelling approach with the triaxial compression test reported by Medhurst (1996) indicated a very close agreement of the results with the laboratory findings. At low confinement, the samples received a typical hourglass pattern of failure, while it transitioned to the typical shear mode of failure in well-defined planes with the increasing confinement. The failure was uncontrolled at lower confinement, but it became gradual with increasing confinement.

Assessment of caved goaf parameters

Model 'II' considered the constitutive behaviour of the goaf material reported by Salamon (1990) and the laboratory test results reported by Pappas and Mark (1994) to develop a standard approach for deriving the model parameters of the Double yield material to simulate the site-specific behaviour of caved goaf in a given geo-mining condition. It simulated the confined uniaxial compression of the caved goaf material considering the initial modulus of goaf material varying from 10-50 MPa and bulking factor of the material varying from 1.1-1.5 in a cylindrical chamber of 365 mm diameter and 305 mm height, as reported in the laboratory test.

The Double yield model parameters were established in terms of density, bulk and shear moduli, angle of internal friction, dilation angle, Poisson's ratio, and the multiplier 'R' associated with the cap pressure. The density of the goaf material was scaled down from the intact rock density considering the conservation of mass and the bulking factor of the goaf material formed upon the caving of the strata within the caving zone. The maximum bulk and shear moduli were estimated from the elastic modulus of the goaf material (Equation 6.6) using standard relation considering Poisson's ratio of 0.2.

Several experimental models were run to establish the relation between cap pressure and stress recovery for different values of the initial modulus 'E_0' and the bulking factor 'b' of the caved goaf. A provisional estimate of the cap-pressure table was made using the Salamon (1990) model for the given value of 'E_0' and 'b' for maximum vertical stress anticipated at the given cover depth. The Double-yield material properties, along with the maximum bulk and shear moduli, were input into the numerical model of the confined uniaxial test to obtain the axial stress versus strain curve at the different stages of loading and compare it with the provisional cap-pressure table. It was observed that a constant ratio lies between the cap pressure and the stress-strain curve for a given set of goaf material properties. The derived ratio was used to obtain the final cap-pressure table for a given set of conditions.

Estimation of Abutment Angle

An in-depth parametric study was undertaken to evaluate the abutment angle that formed along the edge of the chain pillar for different caving profiles of the roof strata in different longwall panels at different cover depths (Model V). The study considered cover depth varying from 350 – 900 m and thickness ratio of the strata within the Caved zone varying from 0.5 to 2.0 for the soft, moderate, and hard strata conditions. The strength properties of these strata were assigned utilising the database from 27 different longwall workings in different coalfields in India.

The three-dimensional numerical modelling study indicated variations in abutment angle from 1 to 70° for different strengths of the strata at the cover depth of 350 – 900 m and face length and thickness ratio of 150 - 250 m and 0.5-2.0, respectively. A statistical model was developed using the results of the 81 parametric numerical models to estimate the abutment angle as the function of cover depth, face length, strength, thickness, and unit weight of the roof layers in the Caved zone. The study showed that when the immediate and the main roof layers are of similar thickness, the bending tendency of the combined strata is almost similar. Hence, the system of roof layers develops a poor bending tendency resulting in a low caving angle and a large abutment angle. However, when the thickness of the main roof is lower, it works as a loading layer for the thicker immediate roof resulting in increased bending of the immediate roof layer. The caving angle of the strata in such a case is higher, which produces a low abutment angle. When the thickness of the immediate roof is lower than the main roof, the main roof does not act as the loading layer. Hence, the two layers undergo independent bending without influencing the bending tendency of the lower layer. Hence, the overall bending of the composite layer is of moderate nature, producing the resultant abutment angle in between the previous two conditions.

The abutment angle varied from 10 to 25° for the decrease in the face length from 250 m to 150 m at the cover depth of 600 m in the moderate strength condition of the strata with the thickness ratio of 1.0. With a change in the cover depth from 350 m to 900 m, the abutment angle decreased from 38 to 5° for the moderate strength condition, face length of 200 m, and thickness ratio of 1.0. However, the abutment angle increased from 8 to 32° for the strength changing from soft to hard at the cover depth of 600 m, face length of 200 m, and the thickness ratio of 1.0. At the cover depth of 600 m, face length of 200 m, and moderately strong strata condition, the maximum and the minimum abutment angle of 18° and 3° were observed for thickness ratios of 1.0 and 0.5, while the abutment angle was 7° for the thickness ratio of 2.0.

The verification of the model outcome through field observations (Das, 2000) confirmed a variable abutment angle under different geo-mining conditions in contrast to its constant value adopted in previous studies. The results were also consistent with the findings of Tulu and Heasley (2012), Hill et al. (2015), and Tuncay et al. (2021), explaining the influence of the cover depth and panel width on the abutment angle.

Factor of Safety of the Chain Pillars

A numerical modelling study of 23 failed, and 20 stable cases of support pillars were conducted considering the control parameters of the post-failure behaviour of the pillars and the Sheorey failure criterion for deriving the triaxial strength properties for different coal seams. The uniaxial compression test for all the cases was modelled (Model IV) considering the Mohr-Coulomb strain-softening (MCSS) failure criterion for coal and elastic material model for roof and floor strata to quantify the failure strengths and distinguish failed and stable cases of the pillars based on their factor of safety (FoS). The study showed that almost all the cases of failed pillars had FoS < 1. The median safety factor for these cases was 0.78, which was subsequently opted as the criterion for the optimal design of chain pillars considering their ultimate loading.

The study confirmed that the pillars having a w/h ratio less than 2.0 had a brittle post-failure behaviour. In contrast, the pillars having w/h of 2-6 showed strain-softening behaviour, and those with w/h of 6-9 showed strain-softening behaviour followed by strain-hardening characteristics after attaining the residual strength because of the reconsolidation of the broken material around the core. The state of failure and mobilisation of the interface at the contact planes in the roof-pillar-floor system also showed a similar behaviour as noted at the specimen scale. The pillar having w/h of 3.6 failed completely up to the core at the residual strength stage, but the slippage of the interface at the core zone was negligible. This observation was similar to the model observed results of the laboratory-scale specimen having a w/h of 4.5. The failed elements around the core and the interface effect enabled sufficient residual strength of the pillar. The pillar had a small elastic core at its peak strength. The failure at the mid-height of the pillar penetrated deeper than the failure at the contact surfaces of the roof-pillar-floor system.

Strength and Deformability Parameters of the Damaged Zones in the Overlying Strata

The models considered the Caved zone of 15 times the extraction height, considering the worst possible bulking factor of 1.07 in Indian geo-mining conditions (Model VI). Four case studies were considered at the cover depth ranging from 50 to 74 m and face length of 120 to 150 m, representing panels ‘W2’ in RVII coal seam at Jhanjra, panel ‘P1’ in Passang coal seam at Balrampur, panel ‘K5’ in Passang coal seam at New Kumda, and panel ‘P2’ in Burhar VIB coal seam at Rajendra Colliery to simulate the expected surface subsidence in these conditions by seeking appropriate constitutive behaviour and material properties of the rock mass in the

‘Fractured’ zone that lies above the ‘Caved’ zone in these workings. The subsidence profile estimated by Saxena (2003) model was used to calibrate the properties of the 5 - 40 m thick ‘Fractured’ zone strata in these cases. The study revealed that the ‘Ubiquitous-joint’ material model with joint cohesion of 125 kPa and joint friction angle of 27° was able to replicate the maximum surface subsidence of 1.47-2.53 m corresponding to the extraction height of 2.2-3.7 m in these conditions. The initial modulus of the goaf material in these cases varied from 4.2-8 MPa. The model observed subsidence profile within the mining zone was closed reproduced by the empirical model. The model observed subsidence profiles at the edges were also in line with the field observations as reported by Singh and Yadav (1995) for the hard strata conditions.

Further study was made to evaluate the constitutive behaviour and model parameters of strata representing the ‘Continuous Deformation’ zone (CDZ) above the ‘Fractured’ zone. Four case studies pertaining to panel 3 in Queen seam at JK5, panel 21 in coal seam ‘I’ of PVK 5, panel 4 in coal seam ‘I’ at VK7, and panel 1 in coal seam ‘I’ at ALP were considered at the cover depth of 188 – 465 m. The experimental modelling using the ‘Ubiquitous-joint’ material model established in Section 6.5, Chapter 6 was used to quantify the maximum extent of the Fractured zone and evaluate the reasonable properties of the Continuous Deformation zone to reproduce the surface subsidence either observed in the field or estimated by the empirical model. Accordingly, the maximum extent of the Fractured zone was limited to 28 times the extraction height, and the strata within the CDZ were modelled as ‘Transversely Isotropic Elastic’ material with E_3/E_1 of 1.72 and G_{33} of 33 MPa. The results of all these models were validated in terms of the cover pressure distance (CPD) or the maximum pressure distance (MPD), maximum stress recovery, load transfer distance (LTD), and side abutment loading profile reported in the literature for similar conditions.

The side abutment stress followed an exponential decay profile with the distance from the panel edge in all the workings. These results were in line with the findings of Wilson (1983). The side abutment load in these works also agreed closely with the estimates of Mark (1987). For supercritical longwall workings, the maximum stress recovery reached the cover pressure, while it was 54-79% of the cover pressure for subcritical workings. The CPD for supercritical workings ranged from 0.33-0.48 times, and the MPD for subcritical workings was 0.12-0.32 times the cover depth, which corroborated well the findings of Smart and Haley (1987), Wilson (1981), King and Whittaker (1971), Choi and McCain (1980), Mark (1987), and Sheorey (1993). The peak side abutment stress varied between 2.26-3.42 times the in-situ vertical stress, which is in close agreement with the typical observations in the Indian coalfields, as reported by Singh and Singh (2009). However, the model observed load transfer distance (LTD) was 1.8-2.7 times greater than the simplified depth-dependent estimates of Peng and Chiang (1984), owing to the strong and massive nature of superincumbent strata in the Indian geo-mining conditions. The other workers, such as Singh et al. (2011) and Larson (2015), also highlighted the influence of the strong and massive strata on the LTD.

Parametric Modelling Study

The Model I was used for evaluating the factor of safety and failure mechanism of the chain pillars for face length varying from 150-250 m, the cover depth varying from 350 to 900 m and different strength of the overlying strata and thicknesses of the strata in the Caved zone. The interfaces along the planes of contact at the roof-pillar and pillar-floor ends were assigned minimum normal and shear stiffness while ensuring compliance with the maximum permissible interface penetration as suggested in the manual. Their cohesion and friction angle values were assigned as 0.18 MPa and 27°, following the approach suggested in Das et al. (2019).

For evaluating the factor of safety of the chain pillar, the coal seam was modelled as 'Elastic' material, while the rest of the strata were considered as 'Mohr-Coulomb' material at the virgin stage. The strata within the Caved zone were assigned the 'Double-yield' material model, and the 'Fractured' zone was assigned the 'Ubiquitous joint' material model. In contrast, the CDZ was modelled as the 'Transversely Isotropic elastic' model. The floor strata were assigned Mohr-Coulomb strength properties considering competent strata formation of the sandstone, which is prevalent in most of the coalfields in India. Due care was taken in defining the abutment angle as per the findings of the study reported in Section 7.6, Chapter 7. The simulation involved the development of gate roads considering a single or double row of chain pillars between the two adjacent panels and their sequential extraction as practised in the field. The size of the chain pillars for the single row configuration of the chain pillars varied from 25 – 100 m in the parametric study. A total of 1296 plain strain numerical models were studied to evaluate the FoS of the chain pillar in each condition.

The modelling results revealed that many input parameters were interrelated, although they seemed independent in the preliminary stage. For example, the abutment angle was considered to be independent of the face length and depth of cover. However, the in-depth study indicated that it is affected by several factors. Under such conditions, the Machine learning (ML) tool was used to explain the complex interrelation between the control variables that affect the stability of the chain pillar in the ultimate stage of loading. This loading stage represented the condition when both the panels on either side of the chain pillar have been mined, and the chain pillar under consideration is beyond the zone of influence of the longwall faces. Thus, it considered the side abutment load being transferred on the pillars due to staged loading due to the sequential extraction of the panels and the damaged zones that form in the overlying strata in response to mining in the respective panels. A similar ML model was also worked out for the double row configuration of the chain pillars, wherein the size of the chain pillar varied from 10 - 47.5 m with respect to the same set of input data.

The modelling results indicated that parameters such as the pillar width, coal strength, abutment angle, and moduli ratio of immediate roof and floor to the coal seam are positively correlated to the factor of safety of the chain pillars, while pillar height, cover depth, face length, caving height, overburden density and modulus of the strata in the CDZ are negatively correlated. Pillar width was the most influential parameter having a positive correlation with the stability of the chain pillar. At the same time, cover depth was the most critical parameter having an inverse relation with the stability of the pillar. Modulus ratio and strength of the immediate roof with respect to the coal seam also played a significant role. The influence of face length, the density of roof layers and the modulus of the overburden strata had a marginal influence on the stability condition of the pillar.

The observed trends for the coal strength, pillar width, modulus ratio, cover depth, face length, and overburden density are broadly in line with the findings of Choi and McCain (1980), Hsuing and Peng (1985), Mark and Bieniawski (1986), and Colwell (1998). As noted by Frith and Reed (2018), the increased spanning capability of the overburden strata over the caved goaf could lead to the increased load on the chain pillar, resulting in its reduced safety factor. The earlier works for the chain pillar design either considered a constant abutment angle or did not include its effect at all. Further, they estimated the strength of the pillar using an empirical formula and used the abutment angle only to determine the pillar load. These studies were not able to assess the influence of abutment angle on the pillar strength. The positive trend of the safety factor of the chain pillar with abutment angle is due to increased pillar strength, resulting from improved confinement, which is in line with the observation of Chokhani (2012). The FoS of the chain pillar was negatively correlated to the caving height owing to an increase in the side abutment stress with the caving height (Rezaei et al., 2015c).

Case Study

ALP Seam I Working

The standard approach developed in this work was used to compare the pillar width practised in the field with the model estimated optimal size for six different mining locations at a cover depth varying from 392-865 m and a face length of 95-250 m. The abutment angle in these workings varied from 3-11°, as estimated using the statistical model developed in this work. In the elasto-plastic model, the coal seam was considered a strain-softening material with its post-failure parameters representing a very large-sized pillar. The strain-softening parameters for chain pillars were assigned according to their w/h ratio following the standard approach.

In ALP, the field size of the chain pillars between panels P1-P2 of 250m width at the cover depth of 465 m was 50 m, while the ML and the numerical model estimated optimal size was 51 m. The field size chain pillar between panels 2 and 3 at the cover depth of 519 m was 63 m, while the ML model indicated optimum size was 58 m, and the numerical model estimated size was 56 m. Similarly, the field size chain pillar between panels 3 and 4 at the cover depth of 567 m was 69 m, while the ML model indicated optimum size was 61 m and the numerical model-based optimum pillar size was 60 m.

The in-depth stress analysis of side abutment loading and stress recovery in the goaf upon staged extraction of the adjoining panels in these working indicated that the peak side abutment stress varied from 1.9 to 2.04 times the in-situ vertical stress while the goaf stress recovery was 76-85% of the cover pressure upon extraction of the first panel. At the ultimate loading stage, the side abutment stress was 2.7-2.8 times the in-situ stress, while the stress recovery in the goaf reached 100% of the cover pressure for the pillar width of 50-69 m.

Although these pillars failed up to 9-12 m along their ribs, the weaker overlying strata suffered a major failure. The stress recovery in the goaf achieved full cover pressure irrespective of the pillar size, as the roof strata could not sustain the highly concentrated stress due to lower strength, and the whole abutment load was ultimately transferred to the goaf. The plot of stress tensor adequately explained the role of confining stress on the stability of the chain pillars. Upon development of the gate road, the stress relaxed zone was formed only in a marginal portion along the ribs of the pillars, while the core of the pillar was only marginally concentrated of stress with respect to the virgin vertical stress. Upon mining of the first panel, the chain pillar developed a non-uniform side abutment load, and the confining stress also shifted accordingly to have further growth of the extent of the failure along the sides of the chain pillar. Upon mining of the second panel, the major principal stress continued to pass through the core of the pillar with readjustment of the confining stress, resulting in failure to the extent of 9-12 m on either side of the pillar. As the roof was comparatively weaker, it failed earlier before the pillar could crush. The abutment stress got redistributed upon failure in the roof. Thus, the integrity of the elastic core in the inter panel chain pillars of width as low as 50 m was still maintained.

The convergence and the lateral deformation of the pillar and coal ribs in the tailgate of the second panel varied between 83-106 mm, 53-78 mm and 17 – 31 mm respectively, in the three workings. The model observed tailgate convergence is in close agreement with the field observed data. The modelling confirmed that it was possible to extract such workings with pillar size of 50 – 60 m at the cover depth of 465 – 567 m without any compromise on the safety of the mine workings.

Moonidih Colliery XVIII Seam Working

Upon mining of both the adjoining panels A4 and A5 of 95 m face length, the field size pillar of 45 m width in the 392 m deep XVIII seam at Moonidih Colliery experienced twin peaks of the side abutment stress with the maximum of 24 MPa, which is 3.2 times of the in-situ stress. The peak stress was realised at a distance of 12.5 m from the centre of the pillar. The maximum stress recovery in the goaf was 57-66 % in the adjoining panels. For the optimum width of 25 m, the goaf stress increased to 84-92%, while the side abutment stress in the pillar increased to 31.7 MPa, which is 4.1 times the in-situ vertical stress. This condition observed peak stress at the centre of the chain pillar. The field size pillar did not show any significant failure in the roof. However, failure reached the core of the optimum size pillar.

The confining stress and the extent of failure along the edges of the pillar showed a similar trend as observed in the ALP working, except that the failure in the relatively stronger roof was initiated after the failure in the coal pillar. The deformation in the gate road varied from 51 -56 mm for the optimum pillar size. These deformation values agree with the field observations for acceptable performance of the chain pillar under given geo-mining conditions. The marginal increase in deformation with the reduction in pillar width from 45 m to 25 m implied that the latter could serve its design function without any compromise in the safety of the workings.

Moonidih Colliery XVI Top Seam Working

The field size pillar of 50 m between panels D12 and D13 in the XVI Top seam of Moonidih Colliery experienced twin peaks of the side abutment stress having a maximum of 52.7 MPa, which is 3.7 times the in-situ stress upon mining both the adjoining panels. The peak stress was observed at a distance of 14 m from the centre of the pillar. The maximum stress recovery in the goaf was 75 to 84% of the cover pressure in the adjoining panels. For the optimum pillar size of 34 m, although the goaf stress received only a marginal increase to 84 to 88%, the side abutment stress in the pillar increased to 67 MPa, which is 4.7 times the in-situ vertical stress. The peak stress was observed at a distance of only 4 m from the centre. The field size pillar did not show any significant failure in the roof. However, the failure reached the core along the contact surface of the roof and the pillar with a reduced pillar size corresponding to its optimum design. The confining stress and the extent of failure along the edges of the pillar showed a similar trend as observed in the previous case. However, the lateral deformation at the pillar and the coal ribs was significantly higher compared to the gate road convergence. A relatively marginal increase in the convergence and the lateral deformation with the reduced pillar size confirmed that the 34 m wide pillar could serve its design function without compromising the safety of the workings.

Moonidih Colliery XV Top Seam Working

The field size single row chain pillars of 60 m width between panels T3 and T4 in 865 m deep XV Top seam at Moohidih Colliery experienced peak abutment stress of 56.8 MPa, which is 3.8 times of in-situ vertical stress, while the failure extended to the core of the pillar during its ultimate stage of the loading. The stress recovery in the first panel was 88% of the cover pressure, while it was 80% in the second panel. Although the pillar failed up to its core, the roof was still stable. However, for the optimum pillar size of 52 m, the peak abutment increased to 76.8 MPa, which is 4.5 times the in-situ stress, and the roof also received failure along with the failure of the pillar. The stress recovery in the first panel achieved the cover pressure, while it was 90% in the second panel. The lateral deformation and convergence in the gate road were significantly higher than the previous conditions owing to significantly higher cover depth. Such conditions demand a proactive supporting strategy to maintain the functional stability of the gate roads.

For double row configuration, the optimal size of the pillar between the panels T3 and T4 was 42 m compared to 52 m for the single row. The stress recovery in the goaf of the first panel was 100% of the cover pressure as observed in the previous case. However, in the second panel, it increased only marginally by 4% for the new configuration of the chain pillar. The chain pillar of reduced size received most of its failure upon mining the adjacent panel. However, its core and the remaining portion facing the middle gate road remained stable. Similar conditions developed for the second pillar upon mining the second panel. However, the gate road deformation increased significantly compared to the single-row pillars.

It may be noted here that this model did not consider any support in the roof. Hence, the resultant deformation may be exaggerated as compared to the supported excavation. Further, the stability of the pillars has been evaluated at its ultimate stage of loading, representing a condition when both the panels have been excavated, and the pillar under consideration is beyond the zone of influence of the front abutment load of the individual panels. Moreover, the field experience in similar conditions in other countries has established that it is possible to maintain acceptable roof conditions in such workings by taking care of the yield zone in the roof and sides of the gate roads. Under these conditions, it is expected that the optimum size pillar of 42 m with the double row configuration would serve its design function of serviceable gate roads and efficient ventilation to the highly gassy workings at such a high depth of cover of the chain pillars.

The cover pressure distance (CPD) in the modelled cases varied from 0.06 - 0.12 times the cover depth. The observed CPD was lower as compared to the previous findings of Smart and Haley (1987), Wilson (1981), King and Whittaker (1971), Choi and McCain (1980), Mark (1987), and Sheorey (1993). It was mainly because of the different considerations to the abutment angle, which ranged from 3-11° depending upon the geo-mining conditions. In comparison, the previous workers assumed a relatively high abutment angle of 18°, 21°, and 31°.

10.2 Conclusions

The following conclusions can be drawn based on the study conducted in this dissertation:

i. A numerical modelling approach has been developed to design optimal size chain pillars for deep longwall workings in Indian geo-mining conditions. It considered a calibrated 'Double-yield' material model for simulating stress recovery in goaf material, 'Ubiquitous joint' model for simulating damage in the 'Fractured' zone, and 'Transversely Isotropic Elastic' model for the 'Continuous Deformation' zone (CDZ). The estimation of abutment angle and the post-failure strain-softening behaviour of different w/h ratios of the chain pillars were also explained through empirical relations.

ii. The abutment angle was not constant across the geo-mining condition of the longwall working. It was negatively correlated with the cover depth and the face length and positively correlated with the strata strength. It also depended on the thickness ratio of the strata within the Caved zone and the face length. Cover depth was the most critical parameter.

iii. The post-failure degradation of the cohesion was positively correlated with the uniaxial compressive strength, w/h ratio, elastic modulus, and the zone size and negatively correlated with the friction angle. The residual value of cohesion was positively correlated with the w/h ratio.

iv. The degradation rate of friction angle was constant, while its residual value was positively correlated with the w/h ratio and negatively correlated with the peak friction angle.

v. The interface along the planes of contact of the roof – pillar and floor – pillar and the zone size of the pillar had a significant influence on the post-failure behaviour of the pillar.

vi. Pillars having a w/h ratio less than 2 showed a brittle failure, while those with a w/h ratio of 2-6 showed a strain-softening behaviour. Pillars with a w/h ratio of more than 6 showed a positive volumetric strain trend in response to the axial strain during the uniaxial loading, confirming its strain hardening behaviour.

vii. The standard approach for simulating the loading behaviour and study of the factor of safety led to the development of a machine learning (ML) based model for the rational design of the chain pillars. The FoS-based design criterion for chain pillars was developed by simulating the failed and stable cases of 43 support pillars in different coal seams in India. The median FoS of 0.78 of the failed pillars represented the optimum size pillars.

viii. For Adriyala Longwall Project workings, the pillars implemented in the field were 12.5-15% wider as compared to the optimum size as estimated in this study.

ix. The pillar width of 25 m proved to be optimum in place of the field size pillar of 45 m for working 95 m wide longwall panels A4-A5 in 392 m deep coal seam XVIII at Moonidih Colliery. The rational size of chain pillar between panels D12 and D13 of 150 m face length in XVI seam working at this mine at a cover depth of 580 m was estimated as 34m compared to 50 m as implemented in the field.

x. The 60 m wide chain pillars in the single row layout between the panels T3 and T4 of 250 m face length in XV Top coal seam at Moonidih Colliery proved to be oversized by 15% compared to the optimum size of 52 m at the cover depth of 865 m at Moonidih Colliery. For double row configuration, the optimal size of pillars was further reduced to 42 m.

xi. The oversized pillars either showed incomplete failure even after the extraction of both the adjoining panels or lesser stress transfer in the goaf area at the cost of wastage of mineral undesirably locked up in the chain pillars. The optimum size pillars not only ensured its controlled settlement during sequential mining of the adjoining panels but also helped in a reasonable stress transfer in the caved goaf that had a more significant role in defining the overall ground control after the extraction of the panels.

xii. The lateral deformation in the gate road and the edges of the chain pillars increased with the increasing cover depth and reduced pillar width. A proactive supporting strategy was required to effectively control plastic deformation and the sustainable serviceability of gate roads in such conditions.

xiii. The concentration of side abutment load for weaker immediate roof conditions led to its failure before the coal pillar could undergo failure, thus, limiting the role of the pillar on the overall stability in such workings.

xiv. The machine learning model for the single and double row configurations of the chain pillars revealed that the factor of safety of the chain pillar is positively correlated with the pillar width, coal strength, abutment angle, and the ratio between the modulus of the coal seam and the roof and floor strata. It showed a negative correlation with the pillar height, cover depth, face length, caving height, unit weight and modulus of the overburden strata.

xv. Except ALP working, the oversized pillars in rest of the cases had an intact core of 24 to 28 m even after extraction of both the adjoining panels compared to approximately no intact zone in the optimal size pillars. In the case of ALP working, the failure in the pillar system was governed by the behaviour of the weak immediate roof.

xvi. The maximum side abutment load varied between 1.78 to 2.83 times the in-situ vertical stress for cover depth varying from 392 to 865 m and face length varying from 95 to 250 m.

xvii. The caved goaf achieved the cover pressure in most of the subcritical deep longwall workings with the optimal size of the intervening chain pillars.

xviii. The distance to the maximum stress recovery in the goaf was 0.06 - 0.12H compared to 0.12 - 0.6H reported earlier.

10.3 Future Scope of Work

The scope for future work is as follows:

i. The field-measured data of stress in the chain pillars and the solid coal blocks can be used for further validation of the numerical and machine learning models.

ii. The numerical modelling outcomes can be further refined as field data become available from the deep longwall workings in the future.

iii. Limited three-dimensional modelling can be considered following the approach suggested in this study to assess the stability of the chain pillar under the front abutment loading of the second panel along with the side abutment loading of the first panel.

iv. A detailed modelling work can be undertaken to design the support system for controlling elasto-plastic deformation in the gate roads under the high depth of cover.