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

Thesis submitted in partial fulfilment for the Award of Degree

Doctor of Philosophy

By

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II

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III

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Abstract

India is witnessing a significant increase in domestic energy demand due to its expanding economy, industrialisation, urbanisation, and population. The projected coal demand is likely to touch 1.5 billion tons in the country by 2030, which is 63% higher than the current demand level. The open-pit mining is staring at several challenges because of numerous reasons. Hence, the mining industry in the country is bound to shift its focus to underground mining to increase production and keep up with the projected future coal demand. Longwall mining is the most efficient mass production technology for the extraction of deep coal seams. Rational design of chain pillars is indispensable to ensure adequate isolation from the adjoining goaf and stability of gate roads for safe access and unhindered production from the longwall faces. In India, the design of chain pillars has not garnered much attention. They are mostly designed following the regulatory provisions for support pillars. The approach of chain pillar design for longwall workings should be different from the approach for the design of support pillars in Bord and Pillar workings because of the fundamental difference in the layout of pillars and their loading conditions. Chain pillars designed using such an approach are generally oversized, leading to a significant mineral loss. The global trend in longwall design is towards longer and wider panels. The design of such panels at high cover depth requires multiple entries to meet the ventilation requirement. Hence, the need is to design the chain pillars with adequate safety by accurately identifying the loading and strength conditions.

In consideration of these requirements, the objectives of the present work were to develop a numerical modelling-based approach for the design of abutment chain pillars for deep longwall workings, conduct a detailed parametric study to identify the critical factors affecting the failure mechanism and stability of the chain pillars, establish a safety factor based criterion for designing abutment chain pillars considering single and double-row layouts in Indian geo-mining conditions, and evaluate the performance of the approach through a few case studies.

The scope of the work was limited to the design of chain pillars with their functional objective of isolation of longwall panels at a cover depth exceeding 360 m. The design of the yielding type chain pillar is beyond the scope of this work.

The methodology used in this study consisted of review of pertinent literature for the estimation of chain pillar stability and considerations in chain pillar design, compilation and analysis of laboratory and field data related to geo-technical, geo-mining, and field experiences for a set of longwall workings in different coal fields in India, development of a modelling procedure to simulate the failure mechanics of the coal specimens and constitutive behaviour of the caved gob material at the laboratory scale, development of three-dimensional numerical modelling procedures to determine the abutment angle formed due to caving of the overlying strata with progressive face advance, development of plain-strain modelling procedures to determine the strength and deformation properties of the damaged overlying strata due to mining and to evaluate the chain pillar stability, development of modelling procedures for simulating failed and stable coal pillars cases and determining the factor of safety-based criterion for chain pillar stability, parametric study of factors affecting FoS of the chain pillars and the abutment angle, development of a standard approach for estimating the post-failure softening parameters of the coal pillars and abutment angle, development of a machine learning-based model to estimate the pillar stability, and verification of the developed approach through case studies.

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 work showed that 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 was also crucial for consideration of 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 workings, the prevailing practice is wholly based on site-specific field experiences.

Simulation of the Complete Stress-Strain Behaviour

The post-failure strength parameters for different coal seams were estimated by 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 (Model III) 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 study confirmed that the pillars having a w/h ratio less than 2 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 failure state 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.

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 of 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 (E_0) of goaf material varying from 10-50 MPa and bulking factor ('b') 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, maximum 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 E_0 and 'b'. 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 a given cover depth. The double yield material property, 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 through three-dimensional numerical modelling (Model V) 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 depths of cover. 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 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 and massive, 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 250m to 150m 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 to 900 m, the abutment angle decreased from 38 to 5° for the moderate strength condition, face length of 200m, 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, face length of 200 m, and the thickness ratio of 1.0. At the cover depth of 600m, face length of 200m, 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.

The Factor of Safety of the Chain Pillars

The modelling study of 23 failed, and 20 stable cases of support pillars were conducted using model IV, considering the control parameters of the post-failure behaviour of the pillars and the Sheorey's failure criterion for deriving the triaxial strength properties for different coal seams. The uniaxial compression test for all the cases was modelled 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 stage.

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

The Model VI considered the Caved zone of 15 times the extraction height, considering the worst possible bulking factor of 1.07 in Indian geo-mining conditions. Four numerical models 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 mine, 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 subsidence profiles at the edges were also in line with the field observations 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 results of 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 CDZ 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_{13} 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). The maximum stress recovery reached the cover pressure for supercritical longwall workings, 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 with 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 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, while the 'Fractured' zone was assigned the 'Ubiquitous joint' 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. Similar to the progressive mining practised in the field, the simulation of mining involved the development of gate roads considering the single or double row of chain pillars between the two adjoining panels. 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 of the input parameters were interrelated, although they seem 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 along with the same set of remaining input data.

The modelling results indicated that pillar width, coal strength, abutment angle, and modulus 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. The modulus ratio and strength of the immediate roof 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 trends observed 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 design of the chain pillar 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 factor of safety 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 Studies

ALP Seam I Workings

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 392-865m and a face length of 95-250m. 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 large 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 1 and 2 of 250 m 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 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 significant 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 observation. 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. A 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 Moonidih 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 compared to the supported excavation. Further, the stability of the pillars has been evaluated at its ultimate loading stage, 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 higher abutment angle of 18, 21, and 31°.

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.

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ANNEXURE V

Notations, Symbols and Abbreviations

a	A dimensionless constant
A_b	Stress in the yielded zone of the pillar
A_p	Cross-section area of the pillar
A_w	Stress deficiency in the goaf area
b	Bulking factor of the gob material
b_i	Represents the exponent of the failure criterion for intact rock
b_m	Represents the exponent of the failure criterion for rock mass
B	Bord width
c	Cohesion
c_{drop}	Drop rate for cohesion
c_j	Joint cohesion
c_{peak}	Peak value of the cohesion
c_{res}	Residual value of the cohesion
C	Constant associated with the zone of influence
C_p	Circumference of the pillar
d	Diameter of the specimen
dd	Dip direction of the plane of isotropy
dip	Dip angle of the plane of isotropy
D	Degree of disturbance
e1	Young's modulus of the plane of isotropy
e3	Young's modulus in the plane normal to the plane of isotropy
e^{ps}	Plastic shear strain
e^{pt}	Plastic tensile strain
e^{pv}	Plastic volumetric strain
e_c^{ps}	Plastic shear strain corresponding residual cohesion value
e_ϕ^{ps}	Plastic shear strain corresponding residual friction angle
E	Elastic modulus
E_0	Initial tangent modulus
E_c	Elastic Modulus of Coal
E_f	Elastic Modulus of Floor
E_i	Elastic Modulus of Immediate Roof

E_m	Elastic Modulus of Main Roof
f^s	Shear yield function
f^t	Tension yield function
f^v	Volumetric yield function
F	Front abutment factor
F_L	Face length
g13	Shear modulus normal to the plane of isotropy
g^s	Shear plastic potential function
g^t	Tension plastic potential function
g^v	Volumetric plastic potential function
G	Shear modulus
G_T	The average value of geothermal gradient
h	Pillar height
h_c	Height of the Caved zone
h_e	Height of the extraction
h_f	Height of the Fractured zone
H	Depth of Cover
k_c	Strength of 25mm (1 inch) cubic coal sample
k	Strength of 0.3m (1ft) cubical coal sample (critical size)
K	Bulk modulus
K (x_i, x_j)	Kernel function
l	Pillar length
L	Longwall panel length
L_D	Development Load Per Unit Length of the Pillar
L_f	Front Abutment Load per Unit Length of Gate Entry
L_s	Side Abutment Load per unit length of gate entry for critical and supercritical panels
L_{ss}	Side Abutment Load per unit length of gate entry for subcritical panels
nu12	Poisson's ratio in the plane of isotropy
nu13	Poisson's ratio in the plane normal to the plane of isotropy
p	A constant for broken coal
p_c	Cap pressure
P	Width of the panel

q	Triaxial constant
R	Multiplication factor
R_0	Critical w/h ratio of the pillar
R_l	Lower limit of RP
R_P	w/h ratio of the pillar
R_u	Upper limit of R_P
S	Pillar strength
S_{3c}	Triaxial strength
S_c	Compressive strength of the coal specimen
t	Thickness of rock bed
T_{IR}	Thickness of the immediate roof
T_{MR}	Thickness of the main roof
V	Pillar volume
w	Pillar width
w_e	Roadway width
w_{ep}	Effective width of the pillar
$\bar{x}$	Width of the yield zone in the pillar
zs	Zone size
α_0	Determines the curvature of the pre-mobilization portion of the curve for $\sigma_3 = 0$
α'	Determines how the pre-mobilisation curvature changes as a function of σ_3
β	Abutment angle (or Shear Angle or Negative Angle of Draw)
β_T	Coefficient of thermal expansion
γ	Average unit weight
γ^p	Current value of the plastic shear strain
γ'	Defines the decay rate of the dilation angle post-mobilisation for non-zero confinement
γ_0	The decay rate of the dilation angle post-mobilisation for zero confinement
γ_m	Plastic shear strain at which peak dilation is achieved
γ_{IR}	Effective unit weight of the immediate roof
γ_{MR}	Effective unit weight of the main roof
δ_{ij}	Kroenecker delta symbol
Δz_{min}	The smallest width of the neighbouring zone in the normal direction

ε	Axial strain
ε_m	Maximum possible compressive strain
ε_P	A constant in Salamon and Wagner (1985) formula
λ	A dimensionless constant
μ_{0m}	Coefficient of the internal friction angle
ν	Poisson's ratio
ξ_i	Positive slack variables
$\rho_{imm.}^{avg.}$	Thickness weighted average of the density of the immediate roof rocks
σ	Stress
σ_1	Major principal stress
σ_2	Intermediate principal stress
σ_3	Minor principal stress or confining stress
σ_c	Compressive strength of the intact rock
σ_{cm}	Compressive strength of the rock mass
σ_h	Average horizontal stress
σ^t	Tensile strength
σ_j^t	Joint tension limit
σ_m	Equivalent tensile strength
σ_{mIR}	Equivalent tensile strength of the immediate roof
σ_{mMR}	Equivalent tensile strength of the main roof
σ_t	Tensile strength of the intact rock
σ_{tm}	Tensile strength of the rock mass
σ_v	Vertical stress
τ_{sm}	Shear strength
ϕ	Dilation angle
ϕ_{drop}	Drop rates of the friction angle
ϕ_i	Initial value of the friction angle
ϕ_j	Joint friction
$\phi_{res.}$	Residual value of the friction angle
$\phi(x)$	Non-linear mapping function

Abbreviations

CPD	Cover Pressure Distance
DISL	Damage Initiation Spalling Limit
CMR	Coal Mine Regulations
FLAC	Fast Lagrangian Analysis of Continua
DGMS	Directorate General Of Mines Safety
MPR	Maximum Pressure Recovery
MPD	Maximum Pressure Distance
FoS	Factor of Safety
LTD	Load Transfer Distance
NEW	Non-Effective Width to Depth Ratio of the Panel
ALPS	Analysis of Longwall Pillar Stability
ALTS	Analysis of Longwall Tailgate Serviceability
CMRR	Coal Mine Roof Rating
HDZ	Height of Destressed Zone
RSI	Roof Separation Index
RQD	Rock Quality Designation
UCS	Uniaxial Compressive Strength
MC	Mohr-Coulomb
MCSS	Mohr-Coulomb Strain Softening
GSI	Geological Strength Index
NURBS	Non-Uniform Rational Basis Spline
GRC	Ground Response Curve
TAT	Tributary Area Theory
RMR	Rock Mass Rating
CDZ	Continuous Deformation zone
ALP	Adriyala Longwall Project
MPR	Maximum Pressure Recovery
MLR	Multiple Linear Regression
SF	Stability Factor Of The Pillar
SVM	Support Vector Machine
SVR	Support Vector Regression
RBF	Radial Basis Function

VAF	Variance Account For
MAPE	Mean Absolute Percentage Error
RMSE	Root Mean Square Error