CERTIFICATE

It is certified that the work contained in the thesis titled "**Numerical Simulation of Support Design Using Rock Bolt in Bord and Pillar Method"** by **RIZWAN HASIM** has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

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DECLARATION BY THE CANDIDATE

I, ***RIZWAN HASIM***, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of ***Prof. B.K. Shrivastva*** and ***Dr. Ashok Jaiswal*** from July – 2014 to December – 2020, at the ***Department of Mining Engineering***, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc. or available at websites and have not including them in this thesis and have not cited as my own work.

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Dedicated to my mother

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(RIZWAN HASIM)

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LIST OF SYMBOLS AND ABBREVIATIONS

MD	Mechanised Depillaring
CM	Continuous Miner
CIL	Coal India Limited
CSIR	Council of Scientific and Industrial Research
CIMFR	Central Institute of Mining and Fuel Research
CMP	Continuous Miner Panel
SECL	South Eastern Coalfields Limited
ECL	Eastern Coalfields Limited
SCCL	Singareni Collieries Company Limited
GDK 5A	Godavari Khani Incline Mine no. 5A
VK 7	Vakilpalli Incline Mine no. 7
CMR	Coal Mines Regulation
DGMS	Directorate General of Mines Safety
FOS	Factor of Safety
RLH	Rock Load Height
BD	Bolt Density
FLAC 3D	Fast Lagrangian Analysis of Continua three Dimentional
FISH	Programming language embedded within FLAC3D
MC	Mohr-Coulomb
MCSS	Mohr-Coulomb Strain-Hardening/Softening
MPa	Mega pascal
GPa	Giga pascal

Kg	Kilogram
m^3	cubic meter
m^2	Square meter
ECL	Eastern Coalfields Limited
FOS	Factor of Safety
S_p	Strength of pillar
σ_v	Vertical stress
σ_p	Stress on pillar
γ	Unit weight of overlaying rock
D	Depth of working
B	Gallery width
H	Working depth
w	Width of pillar
h	Height of pillar
σ_c	UCS of pillar
W	Width of pillar corner to corner
S_1	Strength of in situ cubical coal pillar
σ_h	Horizontal stress
K	Bulk modulus
G	Shear modulus
E	Young’s modulus
ν	Poisson’s ratio
IRB	Instrumented rock bolt
G	grout shear modulus
t	annulus thickness

D	diameter of roof bolt
c	cohesion
Φ	friction angle
τ_{peak}	shear strength of rock/grout interface
I	Moment of Inertia of rock bolt bar
Cs_{nstiff}	Stiffness of the normal coupling spring
Cs_{ncoh}	Cohesive strength of the normal coupling spring
Cs_{nfric}	Friction strength of the normal coupling spring
σ_1	triaxial strength of rock mass
σ_3	confining stress
σ_{cm}	uniaxial compressive strength rock mass
σ_t	tensile strength of intact rock
σ_{tm}	tensile strength of rock mass
RMR	Rock Mass Rating
b	exponent in failure criterion for intact rock
b_m	exponent in failure criterion for rock mass
RBBLS	roof bolt based breaker line support
LHD	Load Haul Dumper
SDL	Side Discharge Loader

ABSTRACT

The trend of Indian underground coal mine is going into mechanisation by adopting continuous miner technology in Bord and Pillar working. The machine has operated in wider gallery size up to 6.6 m for the smooth maneuvering of the machine and fast retreating during the depillaring stage. The conventional method of mining using Load Haul Dumper (LHD)/ Side Discharge Loader (SDL) machine requires gallery size up to 4.8 m. One of the roof support design is established on empirical expression based on geo-mechanical classification of the roof. Various researchers proposed the geo-mechanical classification of roof (Terzagi, 1946, Bieiawski, 1989, 1976 and Barton et al., 1974). CMRI-ISM RMR (Venkatesvarlu et al., 1989) proposed the geo-mechanical classification of roof based on statistical analysis for various underground coal mines in India. The applicability of any empirical approach is limited within the range of the dataset. At that time, the maximum width of gallery 4.8 m was taken into consideration for computed the empirical relationship. Therefore, an extensive exercise is required for designing the support system in the greater width of the gallery. Numerical simulation is one of the appropriate tools for designing roof support.

Rock bolting is more economical than other support systems used in an underground mine, and also its installation is easy compared with others. It saves material and manpower consumption to improve the productivity of the mine. It also reduces the hindrance in the gallery, particularly in continuous miner (CM) operation. Many researchers have been done in support design in the form of mathematical, empirical and numerical approaches. The three-dimensional numerical simulation gives a reasonable understanding to analyse the complex roof strata and bolt interaction. The numerical model indicates that the roof bolts can significantly affect the vertical stress distribution in the bolted area. So, the development of the three-dimensional roof bolt model can substantially benefit the studies on bolt-grout-rock interaction (Cheng, J et al., 2014). Roof support design in mechanised depillaring panels is a challenge due to the faster extraction rate, complex mining structure, and dynamic loading of the overlying strata.

Kushwaha et al., 2010 have conducted an extensive study through numerical simulation in conventional depillaring operations. In this design methodology, a generalized empirical equation has been developed using numerical simulation technique to estimating the required support load density at different places of the face based on geo-technical parameters of the mine and physico-mechanical properties of the immediate roof rocks during mechanised coal pillar mining. The equation depends on various parameters such as RMR, depth, gallery width and stress ratio. The elastic model has been used to estimate the rock load height using a numerical simulation approach. The minimum and maximum principal stress σ1i, σ3i around an excavation are computed, the rock load height can be estimated by safety factor at different points and drawing its contour. In this method, the factor of safety is taken as ≤ 1.5.

The design of support requirements and roof behaviour is dependent on number of parameters. It has been observed that depth, RMR, gallery size and bolt density are the most prominent factor in the stability of the roof based on the literature survey.

The interaction of rock-bolt-grout with the advancement of the goaf line is understood using three-dimensional modelling. The response in terms of axial load exerted on the bolt has been investigated. Roof behaviour has also been analysed at each stage of operation. The study critically investigates roof behaviour at various stages of depillaring operation in Bord and pillar panel.

Critical parameters have been chosen for the assessment of the roof behaviour under varying roof bolt density (bolt pattern) and geo-mining conditions. The methodology has been developed to formulate the simulation scheme for analyzing the stability of the roof under varying geo-mining parameters. The steps involved to achieve the objective of the thesis are preparation of three-dimensional model of bord and pillar panel, calibration of material properties used in the model, validation of the model for two different case studies of mechanised underground coal mining using continuous miner and semi-mechanised SDL/LHD and study of the impact of various parameters. A focused study area is being chosen near the goaf where maximum induced stress is observed. Simulation of the model has been carried out to analyse rock load height during different stages of depillaring operation. Axial load developed on the bolt has also been observed for different bolt patterns. Influences of various geo-mining parameters such as RMR, size of the gallery, depth of seam and different combinations of bolt patterns have been studied. Optimum required rock bolt density at various locations in depillared area has been observed based on the following set criteria

- Bolt length should be more than 30 cm of maximum observed value of RLH.
- Bolt capacity (anchorage strength) should be more than factor of safety (FOS) i.e., 1.5 times of observed axial load developed on the bolt from simulation.

Statistical analysis of data observed by simulated model results gives the mathematical expression of required support load density at a critical location near goaf edge.

A Three-dimension numerical simulation of the bord and pillar system of mining has been carried out to evaluate the performance of the roof bolt. Two cases have been chosen of Indian coal mines worked by bord and pillar system of mining. The representative model of these cases has been simulated and validated with the help of the observed monitored value of instrumented rock bolt during field observation. Total

One hundred and forty four models have been constructed considering different geo-mining parameters, i.e., depth, RMR, gallery width, and bolt density. The response on the bolt in terms of axial load and roof yield has been monitored during depillaring stages. Based on the number of data observed from simulated models, the criteria for suggesting the optimum support design have been proposed based on rock load height and axial load developed on the bolt.

The numerical simulation approach provides an opportunity to develop a guideline for support design. The design guideline has been developed based on the field and simulated study. The result of numerical modelling is analysed using a simple statistical approach to identify the major influencing parameters. The technical relevance of this analysis is examined through the observed facts of the field studies. Finally, on the basis of different correlations under the detailed study of strata mechanics phenomenon, the generalised empirical relationship is developed for the design of the required support system in mechanised depillaring operation.