

DESIGN OF PROTECTIVE BARRIER PILLAR AGAINST LARGE WATER HEAD IN UNDERGROUND COAL MINES



Thesis submitted in partial fulfillment for the
Award of Degree

Doctor of Philosophy

by

ANKUSH GALAV

**DEPARTMENT OF MINING ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005**

17151001

2023

CERTIFICATE

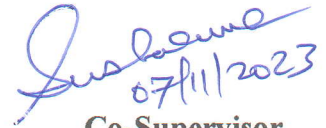
This is to certify that the revised thesis entitled “**DESIGN OF PROTECTIVE BARRIER PILLAR AGAINST LARGE WATER HEAD IN UNDERGROUND COAL MINES**” is being submitted by Mr. **ANKUSH GALAV** in partial fulfillment for the award of Ph.D. in Department of Mining Engineering IIT (BHU), Varanasi is a record of bonafide work carried out by him.

Date of Submission: 07/11/2023



Supervisor

Dr. G.S.P. Singh
Associate professor
Department of Mining Engineering
IIT (BHU) Varanasi

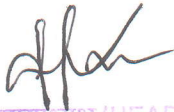


07/11/2023

Co-Supervisor

Prof. Sanjay K. Sharma
Professor
Department of Mining Engineering
IIT (BHU) Varanasi

Forwarded by:



विभागाध्यक्ष/HEAD
खनन अभियंत्रिकी विभाग
Dept. of Mining Engg.
भारतीय प्रौद्योगिकी संस्थान (वाराणसी हिन्दू विश्वविद्यालय)
Indian Institute of Technology (Banaras Hindu University)
वाराणसी (Signature with Seal)

CERTIFICATE

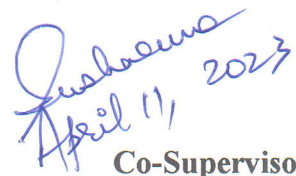
It is certified that the work contained in the thesis titled “**DESIGN OF PROTECTIVE BARRIER PILLAR AGAINST LARGE WATER HEAD IN UNDERGROUND COAL MINES**” by “**ANKUSH GALAV**” has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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.



Supervisor

Dr. G.S.P. Singh
Associate professor
Department of Mining Engineering
IIT (BHU) Varanasi



Co-Supervisor


Prof. Sanjay K. Sharma
Professor
Department of Mining Engineering
IIT (BHU) Varanasi

DECLARATION BY THE CANDIDATE

I, "ANKUSH GALAV", certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of "Dr. G.S.P. SINGH and Prof. S.K. SHARMA" from "JULY 2017" to "APRIL 2023", at the "DEPARTMENT OF MINING ENGINEERING", Indian Institute of Technology (B.H.U), 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 included them in this thesis and have not cited as my own work.

Date: April 10, 2023

Place: IIT (BHU) Varanasi


 (ANKUSH GALAV)
CERTIFICATE BY THE SUPERVISOR(S)

It is certified that the above statement made by the student is correct to the best of our knowledge.


Supervisor
Dr. G.S.P. Singh

Associate professor
 Department of Mining Engineering
 IIT (BHU) Varanasi


Co-Supervisor
Prof. Sanjay K. Sharma

Professor
 Department of Mining Engineering
 IIT (BHU) Varanasi


Signature of Head of Department/Coordinator of School
SEAL OF THE DEPARTMENT/SCHOOL

विभागाध्यक्ष/संयोजक
 खनन अभियंत्रिका विभाग
 Deptt. of Mining Engg.
 भारतीय प्रौद्योगिकी संस्थान (कश्मीर हिन्दू विश्वविद्यालय)
 Indian Institute of Technology (Banaras Hindu University)
 वाराणसी-221005/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Design of Protective Water Barrier Pillar Against Large Water Head
in Underground Coal Mines

Name of the Student: ANKUSH GALAV

COPYRIGHT TRANSFER

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the “Doctor of Philosophy”.

Date: April 10, 2023

Place: IIT (BHU) Varanasi


(ANKUSH GALAV)

Note: However, the author may reproduce or authorise others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author’s personal use provided that the source and Institute’s copyright notice are indicated.

ACKNOWLEDGEMENT

It is with great pleasure and gratitude that I express my sincere appreciation to all those who have contributed to the successful completion of my research work. First and foremost, I would like to express my deepest gratitude to my supervisors, Dr. G.S.P. Singh and Prof. S.K. Sharma, for their invaluable patience, guidance, and feedback throughout my research work. Their unwavering support and encouragement have allowed me to grow as a researcher and an individual.

I would also like to thank my thesis committee members, Prof. N. C. Karmakar and Dr. Amitesh Kumar, for their valuable feedback and support throughout this journey. I would also like to thank Prof. Pramod K Jain, Director, IIT (BHU) Varanasi and Prof. Suprakash Gupta, Head, Department of Mining Engineering, for their unwavering support throughout my research work. I want to express my sincere thanks to Coal India Limited for funding this study and to the management of BCCL, ECL, and SECL for providing the necessary field data that were crucial inputs for this investigation.

I want to thank my friends Mr. AS Chauhan, Mr. V Singh, Mr. R Pandey, and Mr. R Kumar for their unconditional support and love. Their unwavering belief in me and constant encouragement have been instrumental in my research journey. I would also like to express my special thanks to Dr. B Behera and Dr. SK. Sahoo, my seniors and, most importantly, great friends Dr. A Yadav, Mr. G Gupta, Mr. A Chaturvedi, and Mr. S Govind for their invaluable support and guidance during various challenging situations throughout my journey.

Lastly, I owe my parents, brother, and wife a debt of gratitude for their continuous support and trust in me. This research work would not have been possible without their unwavering support and encouragement. Their presence and love allowed me to carry out this research work without worrying much about my responsibilities.

Once again, I express my heartfelt appreciation and gratitude to everyone who has contributed to the successful completion of this research work.


(Ankush Galav)

DEDICATION

To
my father, *Shri Ravindra Kumar Galav*,
and
my wife, *Shrimati Archana Galav*.

List of Tables

	Page No.
1.1. Geo-mining conditions of the PWBP in Indian coal mines	6
2.1. Existing design approaches	14
2.2. Significant mine disaster due to inundation	22
2.3. Permeability relationships by various researchers	35
2.4. Categorization of rock permeability	36
2.5. Mobility coefficient of coal	37
4.1. Interface properties used in the models	69
4.2. Coal properties for Indian coal seams	70
4.3. Best fit cases of CD, CR, FD, and FR for strain-softening behaviour of coal	76
5.1. Baseline data of rock mass properties	83
5.2. The range of various parameters	84
5.3. Rock mass strength properties used in FLAC 2D modelling	98
6.1. Classification of the Severity of water seepage rate in Indian Coal Mines	125
6.2. ZoPVS and seepage rate across PWBP subjected to water head of 100 % of depth	126
6.3. Analysis of Seepage Rate Characteristics of Pillar System	129
6.4. Desired width for controlled flow through the pillar system	131
6.5. Estimates of rational pillar widths and desired water head at different cover depths	135
7.1. Rock mass data for the numerical modelling of Satgram Incline mine working	146
7.2. Hydro-mechanical indicators of PWBP at Satgram Incline mine	151
7.3. Rock mass data for numerical modelling of Lower Kenda mine	153
7.4. Hydro-mechanical indicators of PWBP at Lower Kenda mine	156
7.5. Estimation of water seepage through overburden in Lower Kenda Mine	158
AI.1. Numerical modelling results of ZoPVS	192
AII.1. Numerical modelling results of seepage rate through pillar only	194
AIII.1. Numerical modelling results of seepage rate through roof only	201
AIV.1. Numerical modelling results of seepage rate through floor only	209
AV.1. Numerical modelling results of seepage rate through pillar and roof	217
AVI.1. Numerical modelling results of seepage rate through pillar and floor	239
AVII.1. Numerical modelling results of seepage rate through pillar system	261

List of Figures

	Page No.
1.1. A representative sectional view of PWBP in underground coal mines	3
1.2. Width of PWBP in Indian coal mines	8
1.3. Depth vs. pillar width for protective water barrier pillars in Indian Coalfields	9
1.4. Prevailing water head vs cover depth in different mines	10
2.1. Sectional view showing vertical stress redistribution and distinct zones in a pillar	16
2.2. Plan view of the four distinct zones in a coal sample of w/h=12	17
2.3. The three zones in the pillar	17
2.4. Stress-strain characteristics and failure behaviour of an in-situ pillar of 2 m width and 1 m height at different stages of loading	19
2.5. Effect of w/h ratio on the constitutive behaviour and failure mode of Pillar	20
2.6. Laboratory observed stress-strain behaviour of Kenda Seam specimens	29
2.7. Stress-strain-permeability for coal samples	34
2.8. Weakening coefficient depending on moisture content	39
3.1. Research methodology	45
3.2. Methodology of numerical simulation for the mechanical-hydraulic coupled modelling of Protective Water Barrier Pillars	48
3.3. Schematic diagram of model geometry	50
3.4. (a) Model geometry showing origin (0,0), x and y axes, and uniform zone size, (b) magnified part of MZOI	52
3.5. Model geometry showing mechanical and hydraulic boundary conditions	58
4.1. Material Testing System (MTS) facility used for coal testing at IIT (BHU), Varanasi	66
4.2. Laboratory observed stress-strain behaviour of coal samples for a w/h ratio of 0.5 -10	67
4.3. zones identified on the top end surface of a coal sample of w/h=10	67
4.4. Schematic sketch of cohesion variation with plastic shear strain	71
4.5. Schematic sketch of friction angle variation with plastic shear strain	71
4.6. Methodology for estimating the best-fit strain softening rule	73
4.7. A comparative plot of the model and laboratory observed stress-strain behaviour of Kenda Seam coal specimens having a w/h ratio of 0.5-13.5 and zone size of 0.5 mm	74
4.8. Volumetric strain vs axial strain for w/h ratio 0.5-13.5 and zone size of 0.5 mm for Kenda Seam	75
5.1. Volumetric strain across pillar width at a cover depth of 100, 250, and 350 m	86

5.2. ZoPVS vs cover depth plot for pillar width of 30 m and 60 m	87
5.3. Seepage rate vs cover depth plot for a constant water head of 125 m for 30 m and 60 m wide barrier pillars	88
5.4. Seepage rate vs cover depth for water head of 50 % of cover depth for 30 m and 60 m wide barrier pillars	89
5.5. Volumetric strain across the pillar for 30, 60, 90, and 120 m wide PWBP	90
5.6. ZoPVS vs PWBP width	91
5.7. Seepage rate vs PWBP width	92
5.8. Seepage rate vs permeability	93
5.9. (a) Average vertical stresses (b) Average horizontal stresses (c) Induced permeability, and (d) Volumetric strain contour across different widths of barrier pillar of 3 m height and soft coal at a depth of 350 m	96
5.10. Seepage rate vs water head	97
5.11. Seepage rate vs rock mass strength	99
5.12. Seepage rate for different flow regimes	100
6.1. Estimated vs. model observed ZoPVS	106
6.2. Correlation between modelled and estimated seepage rate through the pillar-only	110
6.3. Correlation between modelled and estimated seepage rate through the roof-only	113
6.4. Correlation between modeled and estimated seepage rate through the floor-only	115
6.5. Correlation between modelled and estimated seepage rate through pillar and roof	118
6.6. Correlation between modelled and estimated seepage rate through pillar and floor	121
6.7. Correlation between modelled and estimated seepage rate through pillar system	124
6.8(a). Seepage rate and ZoPVS for varying pillar width in hard rock conditions at a cover depth of 100 m for different water heads	132
6.8(b). Seepage rate and ZoPVS for varying pillar width in soft rock conditions at a cover depth of 100 m for different water heads	132
6.9(a). Seepage rate and ZoPVS for varying pillar width in hard rock conditions at a cover depth of 250 m for different water heads	133
6.9(b). Seepage rate and ZoPVS for varying pillar width in soft rock conditions at a cover depth of 250 m for different water heads	133
6.10(a). Seepage rate and ZoPVS for varying pillar width in hard rock conditions at a cover depth of 350 m for different water heads	134
6.10(b). Seepage rate and ZoPVS for varying pillar width in soft rock conditions at a cover depth of 350 m for different water heads	134

6.11. Flow chart illustrating the design of PWBP	137
6.12. Suggested approach for assessment of the adequacy of existing PWBP	139
7.1. Geographical location of mines under study	143
7.2. Joint mine plan showing the minimum barrier thickness of 60m between the Satgram Incline working and abandoned waterlogged Jamuria AB Pit Mine	145
7.3. Numerical model of 60 m wide PWBP at Satgram Incline mine	147
7.4. Profile of vertical (a) and horizontal (b) stresses induced in the PWBP in mechanical and hydraulic loading conditions	148
7.5. Pore pressure profile across the pillar	149
7.6. Flow vectors of water seepage in the PWBP at Satgram Incline mine	150
7.7. Seepage rate and ZoPVS for varying pillar width for Satgram incline	152
7.8. Joint mine plan showing the minimum barrier thickness of 30m between the Lower Kenda Mine and the abandoned waterlogged working of Haripur Colliery	154
7.9. Seepage velocity vectors across the PWBP at Lower Kenda mine	155
7.10. Seepage through coal pillar and washed out infill material (a,b) and gushing of water through roof bolts near PWBP (c,d) at Lower Kenda mine	157
7.11. Seepage rate and ZoPVS for varying pillar width for Lower Kenda mine	159