1. Introduction

1.1 General

India is the second-largest coal producer and consumer, with the fifth-largest coal reserves in the world. This fossil fuel contributes to more than 65% of annual power generation in this country. Since the nationalisation of the coal mining industry, the national policy has aimed to enhance indigenous production of fossil fuels for energy security and enhanced growth of the country. As a result, while annual production increased from 80 to 778.2 million tonnes in the last forty-seven years, the share of underground coal production decreased from 20 to 4.5% during this period (Provisional Coal Statistics, 2022; Ministry of Coal, 2023). The significant contribution to production comes from mega opencast projects, many of which produce nearly 18–20 million tonnes per annum. However, this production trend is not likely to continue for a very long period because of the near depletion of shallow depth reserves, severe scarcity of land, and the extreme societal pressure against the expansion of most existing projects.

On the other hand, billions of tons of prime coal are locked in developed pillars in underground workings under varying geo-mining conditions. The mine personnel, machinery, and natural resources are at high risk of dynamic goaf settlement, fire, and inundation. In Chinese coal mines, these issues form the second leading cause of death and economic losses (Yao et al., 2012). Various disasters of mine inundation worldwide have resulted in thousands of deaths and enormous financial losses. The overall situation calls for systematic development of know-how to successfully implement mass underground mining methods for sustainable national growth.

Intact coal blocks are left unmined to provide a hydraulic barrier for controlling water inrush and supporting the overlying roof, designated as protective water barrier pillars (PWBP). The primary purpose of a PWBP is to provide adequate isolation from a waterlogged area to active mine working and protect the active mine from the danger of inundation. Several underground coal mines face a high risk of inundation from waterlogged workings due to the inadequate size of barrier pillars. The inflow of water from the reservoir formed due to the accumulated water in the abandoned mine creates a physical hindrance to coal production as it increases the requirement of daily water handling in the active mine working. A massive influx of water in a short period may cause mine inundation. The study conducted by Job (1987) in British coal mines and Das et. al. (2016) in Indian coal mines revealed that insufficient width of PWBP is a crucial reason for inundation from abandoned water-logged workings in underground coal mines. Providing a suitable water barrier is the predominant practice for protection against such a danger.

The accumulation of water in old workings can occur through seepage from surface water bodies, aquifers, and geological discontinuities during the rainy season, apart from the pumped-out water from active mine workings. A water barrier pillar (Figure 1.1) effectively controls seepage and water inrush from a waterlogged old working to the adjacent active mine. It isolates the active working from a water-filled worked-out area. When the hydraulic pressure due to the water head in the old abandoned workings exceeds the threshold pressure of the barrier pillar, the protective water barrier pillar fails to contain the water (Singh et al., 1982). The slow and steady inflow of water across the protective water barrier pillar gradually becomes continuous and heavy, creating a potential hazard of mine inundation. Such heavy seepage and the sudden inrush of water from an abandoned mine working or other major sources in the active working mine constitute a significant concern for the safety and economy of coal production (Yao et al., 2012; Yin et al., 2015).

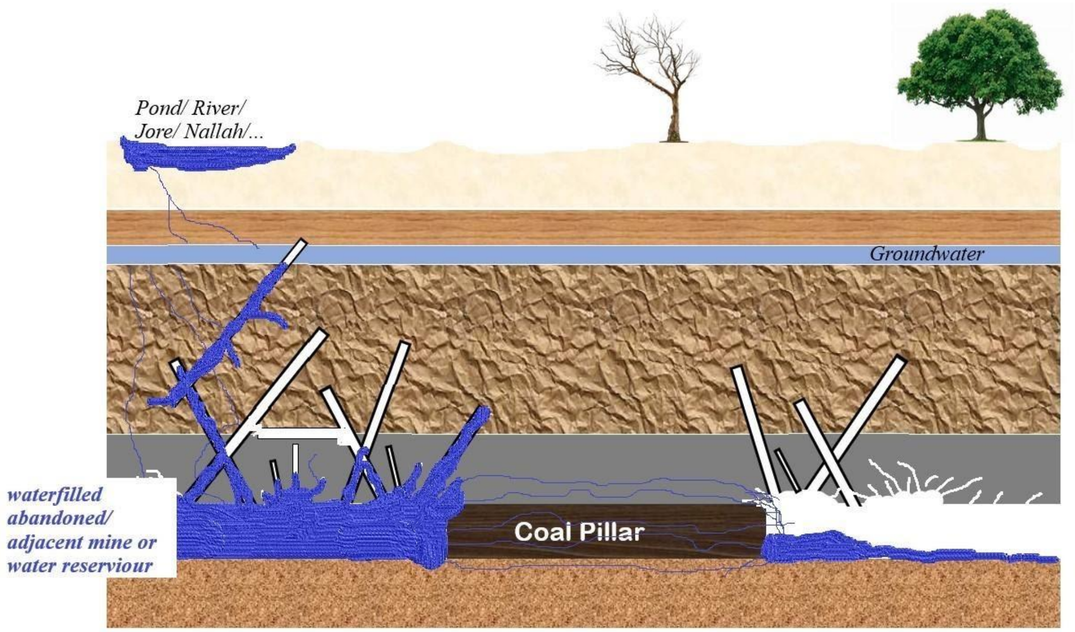

Figure 1.1. A representative sectional view of PWBP in underground coal mines

Practical experience suggests that pillars with lesser width are prone to sudden failure. Bagdigi Colliery in the Jharia Coalfield, India, was operating an underground mine with an incompetent PWBP at a cover depth of 240 m. The width of the barrier pillar got reduced to 20 m, while some reports suggest its reduced width of 10 m only at failure (DGMS, 2003). A routine blasting in the nearby face destroyed the barrier between this mine and the abandoned water-logged Jairampur Colliery. The inundation disaster caused the loss of life of 29 miners working in Bagdigi Colliery. The Kolkata edition of the Times of India (an English daily newspaper), dated 16 February 2001, reported this disaster in the following words:

“The proverbial goose that lays golden eggs is slaughtered here every day. With the losses of Bharat Coking Coal Ltd (BCCL) amounting to a staggering Rs 2 crore a day, its managers are under tremendous pressure to meet their annual targets, come what may so much so that safety norms are thrown to the winds. The Bagdigi Colliery had a target of 1.8 lakh tonnes this financial year. It had achieved only 1.2 lakh tonnes. To get the remaining 60,000 tonnes, even the mandatory 60 metre barrier separating Bagdigi from the water-logged and abandoned Jairampur mine was ignored.” The Economic and Political Journal (2001) noted that “Instead of learning the lessons from Chasnala and Gaslitand tragedies, the mine management has been reducing the gap between underground barriers” “A routine blasting destroyed the underground barrier between Bagdiggi and Jairampur Collieries…”

Regulation 150(3) of the Coal Mines Regulation 2017 (DGMS, 2017) prohibits mining within 60 m of abandoned or adjoining mines. Explicit permission and intensive monitoring are required while working within 60 m of the water-filled area in a mine. The protective barrier pillar of 60m width is considered 'adequate', but the mines are often allowed to have a smaller size. The width of PWBP was derived through the empirical experience without considering the effects of cover depth, water head, rock characteristics, and geological discontinuities. In the absence of any scientific approach, mines are operating at an unknown level of danger from inundation hazards dealing with a huge makeup of mine water and incurring financial losses every day.

Currently, there is no reliable approach to assess the behaviour of PWBP subjected to an available water head. Several analytical and numerical methods have been used to investigate the load and strength of barrier pillars. These approaches focus only on the mechanical performance of the barrier pillar and ignore its hydraulic performance (Bunnell, 2010). It is understood that the width of the pillar and the induced fractures play a dominant role in its performance. The smaller width of the barrier pillar subjected to a large water head has always manifested heavy seepage rate and a strong possibility of inundation. Hence, a conservative approach is to have a squat pillar with a width/height ratio greater than 10. However, the experience from the various mining sites also indicates the need for evaluating the performance of slender and intermediate pillars.

An in-depth research-based guideline can be helpful in the rational design of new barrier pillars and validate the adequacy of existing barriers against a known water head under a given geo-mining condition. It will enable the mines to deal with the impending risk confidently due to the enhanced reliability of design and safety to the best possible standard.

In this thesis, a scientific methodology has been developed for the rational design of protective barrier pillars for underground coal mines in Indian geo-mining conditions. It proposes a steady-state hydro-mechanically coupled numerical modelling approach for assessing the hydro-mechanical performance of protective water barrier pillars (PWBP). A seepage rate severity classification has been proposed based on the field study of various coal mines in different coalfields in India. A parametric study has also been conducted to quantify the influence of different control parameters on the mechanical and hydraulic performance of the protective pillar. The results have been validated using case studies of Satgram Incline and Lower Kenda mines having minimum pillar widths of 30 and 60 m at a cover depth of 84.5 and 134.5 m, respectively. Based on the findings of the work, criteria for the rational design of PWBP have been proposed.

1.2 Background

A random survey was conducted in the different underground coal mines in India. The conditions of the existing protective water barrier pillars are summarised in Table 1.1. The study revealed that the barrier pillar width ranged from 13.5–650 m at a cover depth of 18–300 m with a water head of 10–206.7 m, while the water seepage rate ranged from negligible to 264.6$\times 10^{-3}$ m^3/s/km (4200 GPM/km).

Table 1.1. Geo-mining conditions of the PWBP in Indian coal mines

Sl. No.	Mine_Adjacent Mine	Depth, m	Width, m	Water Head, m	Seepage Rate, 10^{-3} m^3/s/km
1.	Sonepur Bazari_RVIII Seam	18	200	18	Negligible
2.	Siduli_RVIII Seam	25	110	25	Negligible
3.	Mahamaya UG Mine_Mahan OCM	127	125	100	38
4.	Dhelwadih UG Mine_ Singhali UG Mine	158	25	115	139
5.	Mahusudhanpur 7Pit & Incline_Khas Kajora Colliery	59	60	59	Negligible
6.	Sonepur Bazari_RVII Seam	71	200	71	Negligible
7.	Porascole Colliery_CL Jambad Colliery	72	26	72	32
8.	Bankola_RVIII Seam	78	60	78	Negligible
9.	Khandra_RVIII Seam	78	650	78	Negligible
10.	Singhali UG Mine _ Bagdeva UG Mine	80	25	80	221
11.	Sonepur Bazari_RVIIA Seam	91	200	91	Negligible
12.	Patmohana Colliery _ Dhemomain Incline_RVIII Seam	92	45	92	158
13.	Madhabpur Colliery_ Naba Kajora Colliery	93	10	93	Not Available
14.	Madhabpur Colliery_ Parasea 6&7 Incline	93	20	93	Not Available
15.	Madhabpur Colliery_ Nabakajora Colliery	93	60	93	Negligible
16.	Madhabpur Colliery_ Lachipur Colliery	93	60	93	Negligible

17.	Siduli_RVII Seam	101	62	101	Negligible
18.	Central Kajora Colliery_Lachipur Colliery, Ghanshyam Colliery, Madujore Colliery	104.5	15	104.5	Not Available
19.	Gayatri UG mine_ Rehar UG Mine	106.5	43	106.5	158
20.	Patmohana Colliery _West Chinakuri Colliery-III_R-VIII Seam	109	40	109	63
21.	Nabakajora Colliery_Lachipur Colliery	110.5	15	110.5	Not Available
22.	Siduli_RVIIA Seam	119	180	119	Negligible
23.	Rajnagar RO_Handidhua UG Mine	120	50	13	126
24.	Naba Jambad Project_CL Jambad Colliery	120	11.5	110	Not Available
25.	Rajgamar 4&5 Incline_North Rajgamar 6&7	125	120	15	252
26.	Rajgamar 4&5 Incline_South Pawan Incline	130	60	32	189
27.	Bagdeva_G-III Bottom Seam	136	22	24	51
28.	Bankola_RVII Seam	140	50	140	Negligible
29.	Khandra_RVII Seam	140	650	140	Negligible
30.	Dhemomain Colliery_North R.B. Seam_ R-VA Seam	150	180	150	13
31.	Porascole Colliery_Madhusudanpur 3&4 Pit & PSC (E)__Kajora_RIX Seam	159.5	26	159.5	46
32.	Bankola_RVIIA Seam	164	50	164	Negligible
33.	Khandra_Khandra_ RVIIA Seam	164	650	164	Negligible
34.	Rajnagar RO_4A Seam	167	20	67	265
35.	Rajnagar RO_Hingir Rampur Colliery UG Mine	175	42	141	152
36.	Jamabad UG Colliery_ Parasea Colliery	200	17.5	200	Not Available
37.	Porascole Colliery_Moila & PSC (E) Colliery_Jambad_ RVIII Seam	207	16	207	23
38.	Porascole Colliery_Madhusudanpur 3&4 Pit & PSC (E)__Jambad_RVIII Seam	207	13.5	207	46
39.	Parbelia Colliery_Hijuli_RVIII Seam	212	60	10	7
40.	Chinakuri Mine- III_Patmohana Colliery	300	60	105	7

Out of 40 mines included in this study, more than 50% of the mines were maintaining PWBP of less than 60m width (Figure 1.2), as required under the statutory provisions of CMR. In several cases where the width of the barrier was less than 45m, the underground workings were experiencing a high seepage rate through the PWBP in the presence of the high water head and cover depth. There is an urgent need to assess the hydro-mechanical stability of the protective water barrier pillars in all such conditions. In addition, adequate measures are required to avoid the inundation disaster in active mine working.

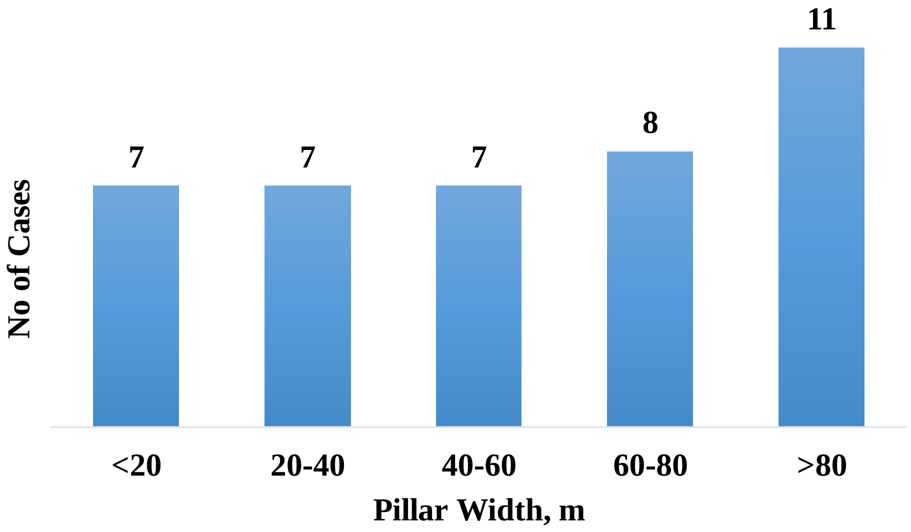

Figure 1.2. Width of PWBP in Indian coal mines

The plot of cover depth vs. the barrier pillar width did not show any meaningful correlation (Figure 1.3). The plot of the water head acting against the existing PWBP at different cover depths revealed that the maximum water head was as high as the cover depth in several workings (Figure 1.4). The random survey also showed that while the nominal size of the PWBP varies from 10–650 m, the pillar height varied only between 2.5–3 m. A barrier of

200 m width at a cover depth of 18–91 m and 650 m width below the cover depth of 78–164 m experienced no seepage through it. A large amount of coal is locked up in such a barrier. Hence, the design of PWBP needs to be rationalised based on scientific considerations, especially the safety and techno-economics of the structure. There are several workings where the regulatory requirements have not been met, and the efficacy of the barrier pillar against the prevailing water head has also not been verified. Several mines are operating with unverified widths or pillars with a significantly lower or higher dimension w.r.t. the legislative provision.

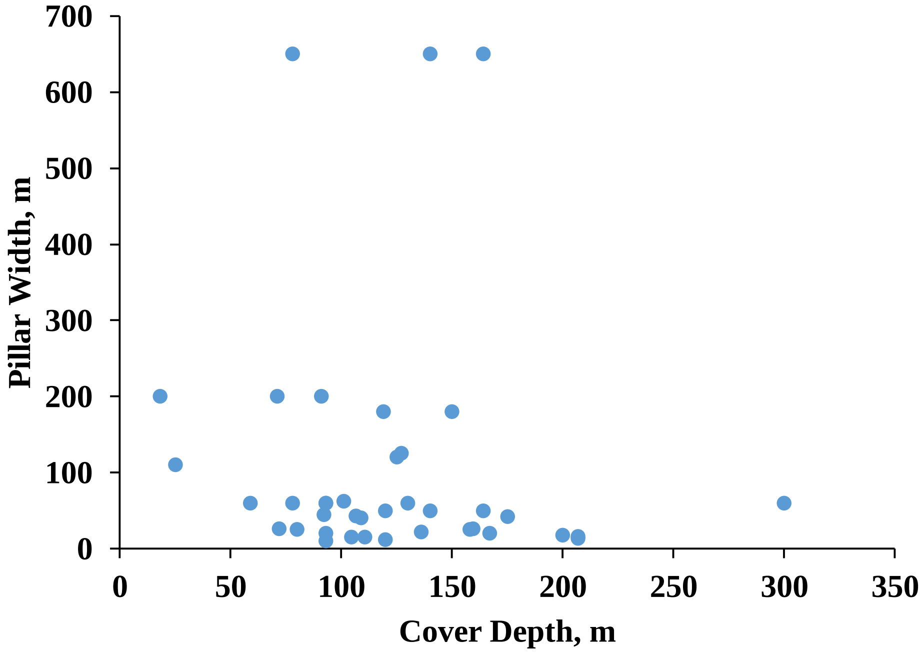

Figure 1.3. Depth vs. pillar width for protective water barrier pillars in Indian Coalfields

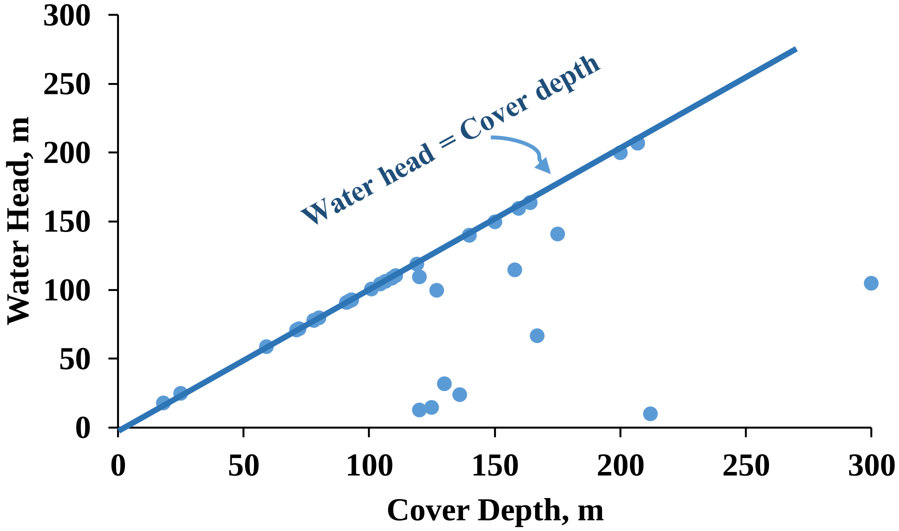

Figure 1.4. Prevailing water head vs cover depth in different mines

1.3 Objective and Scope

The main objective of this work was to develop scientific criteria and guidelines for the design of protective water barrier pillars (PWBP) for different geo-mining conditions considering the different strength and flow regimes. The collateral objectives of the work were to:

- examine the mechanisms of loading and failure of PWBP
- develop an understanding of mechanical and hydraulic performance of PWBP with the change in water head, and
- to assess the rational size of barrier pillar width for different geo-mining conditions

The scope of the present work is limited to the assessment of induced permeability and water seepage rate characteristics through the pillar and their combined impact on the hydro-mechanical performance of the pillars at water head and cover depth varying from 100-350 m.

1.4 Methodology

The research methodology of this work comprised of field survey, literature review, laboratory testing, development of the numerical model, parametric study, development of design criteria, and model validation. An intensive field survey and literature review were conducted to compile pertinent information about existing PWBP, prevailing design methods, and data for the parametric study. The outcome of the numerical modelling-based parametric study was considered along with the field experience to develop the design criteria for evaluating the hydro-mechanical performance of the PWBP. The findings have been validated for two case studies in Indian coal mines.

1.5 Organisation of the Thesis

Chapter 1 introduces the research work and its importance for underground coal mines. It comprises a general introduction, background of this research work, its objective, research methodology, and thesis organisation.

Chapter 2 reviews literature related to global experiences of approaches to PWBP design, critical mine disasters due to inundation, the mechanical stability of the pillar, the effect of w/h ratio on the pillar design, strain softening behaviour of the pillars, the effect of interface on the pillar design, and regulatory provisions for Indian coal mines.

Chapter 3 describes the methodology and the scheme of numerical modelling of the mechanical and hydraulic performances of PWBP.

Chapter 4 describes the simulation of the strain-softening behaviour of coal pillars. The post-failure behaviour of coal specimens established from laboratory testing is simulated to develop a representative statistical model for estimating the strain-softening parameters for numerical simulation of the field scale pillars in different conditions.

Chapter 5 reports the results of the parametric study. It describes the influence of different geo-mechanical and hydraulic parameters, such as cover depth, pillar width, rock-mass strength, permeability, water head, and flow regimes, on the hydro-mechanical behaviour of PWBP.

Chapter 6 provides the criteria for evaluating the hydro-mechanical adequacy of PWBP and the design criteria for assessing its rational size for acceptable long-term performance in given geo-mining conditions.

Chapter 7 validates the numerical model findings and the proposed design criteria. The results of two site-specific cases and their field observations have been examined and compared with the findings of the generalised models obtained from the parametric study. The seepage rate observations and their severity in the field have also been validated.

Chapter 8 presents a discussion of the results to draw inferences on various aspects associated with the design of PWBPs. The findings have been inferred against the existing know-how to provide further insight into the subject.

Chapter 9 concludes the findings of this work and the scope of future work.