Chapter 1

1. Introduction

Energy demand in India is expected to see a steep rise due to expanding economy, industrialization, urbanization, and rising population. Although the share of coal in the overall energy basket is likely to decline steadily, the coal demand in the country is yet to reach its summit (Press Information Bureau, 2022). The projected coal demand is likely to touch 1.5 billion tons in the country by 2030 (Economic survey, 2022), which is 63% higher than the current demand level.

In the past, open-pit mining has majorly contributed to the total coal production in the country. However, this method is staring at several challenges because of depletion of shallow depth coal reserves, increasing environmental concerns, unavailability of land for expanding existing projects and dumping huge volume of overburden in the current projects. 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.

The two most commonly used methods for winning coal from beneath the ground are Bord and Pillar & Longwall. However, the former has a limited mechanisation scope and poor productivity. Bord and Pillar mining is not practised to extract deep-seated coal seams due to the low extraction ratio and ground control challenges due to high vertical stress combined with the low coal strength and the need for maintenance of several openings. The longwall method is the most efficient mass production technology which can stand up to all these challenges.

The first longwall was introduced in India way back in the year 1978. However, the method has struggled to gain prominence in the country due to erroneous planning and site election

(Ghosh, 2003; Islavath et al., 2016; Singh, 2007). As the underground mining is closing towards the deeper reserves, one of the major challenges is the design of chain pillars to ensure adequate isolation from the adjoining goaf and stability of gate roads for safe access and unhindered production from the longwall face throughout the life of the panel.

One or more rows of chain pillars are left between panels to ensure the serviceability of gate roads. The stability of these pillars is critical for the success and safety of the longwall face. In Europe and occasionally in China (Inner Mongolia), rib pillars in the form of continuous coal blocks (without crosscuts) are retained between successive longwall panels (Bai et al., 2017). In other parts of the world, including the USA, India, Australia, South Africa, and China, chain pillars are employed between two longwall panels. The design of the chain pillar system has evolved over the years. Chain pillars in the form of yield pillars, abutment pillars, and numerous other configurations, including combinations of abutment and yield pillars, have been adopted so far. In fact, the functional stability of the pillars has garnered so much attention that the mechanical stability of the pillar has been ignored many a time.

In China, a row of yield pillars in conjunction with highly reinforced gate roads is often designed to ensure the serviceability of entries. In contrast, a row of abutment pillars is generally constructed between successive longwalls to ensure the gate road stability in India, South Africa, and Australia. In the USA, three entry system consisting of two rows of chain pillars is the most common as this is the minimum number of gate entries required as stipulated by their law to develop the panel entries. However, with increasing panel length, four entries consisting of three rows of chain pillars have become the rule so that the minimum required air quantity can be provided to the face at any distance from the main entries. Sometimes, the gate road system consists of four rows of chain pillars. These chain pillars generally have the configuration of abutment-abutment, yield-abutment, and abutment-yield in case of two rows, and abutment-abutment-abutment, abutment-yield-yield, abutment-abutment-yield, yield-

yield-abutment, and abutment-yield-abutment in case of three rows of chain pillars. None of the above configurations has successfully maintained the gate road stability. However, the abutment-yield configuration reduces the abutment pressure significantly on the next panel due to a cleaner caving line along the tailgate entry. In the western U.S., two and single-entry systems have been employed, but they incurred high maintenance costs (Peng and Chiang, 1984).

Historically, chain pillars in U.S. mines are designed based on either a hit-and-trial basis or borrowed from the successful design of other mines (Listak et al., 1988). For example, yield pillars in the various arrangements of the chain pillars are generally 9m, 12m and 15m wide for varying depth of cover, geo-mining conditions, and geotechnical properties of the superincumbent strata (Barron et al., 1994). Mark and Bieniawski (1986) developed an empirical method called 'Analysis of Longwall Pillar Stability (ALPS)' to design gate road systems encompassing abutment pillars based on field measurements and mining practices of the U.S. The method considers the tailgate stability while it is an active part of the longwall mining as the design criteria.

In Australia, the design of chain pillars has been based on the approach primarily developed for Bord and Pillar mining (Seedsman et al., 2005). This approach considers pillar stability as the designing criteria. The pillar stability is evaluated using the safety factor, wherein Galvin et al. (1999) formula estimates the pillar strength. Colwell (1998) developed an empirical approach called 'Analysis of Tailgate Serviceability (ALTS)' in a similar line to 'ALPS' method (Mark, 1990; Mark et al., 1994) by calibrating the loading parameters such as abutment angle and the ratio of the front to side abutment loads for Australian conditions and mining practices.

In India, the design of chain pillars has not garnered much attention. They are designed based on Regulation 111 of the Coal Mines Regulations (DGMS, 2017). However, this regulation provides guidelines exclusively for designing support pillars in the Bord and Pillar workings. The regulation stipulates that the pillar size should not be less than 48 m (c-c) for extraction height of 3 m, gallery width of not more than 4.8 m, and cover depth exceeding 360 m. This necessarily means that for cover depths of 400 and 800 m, the pillar width can be 48 m, which may imply that either the pillar is oversized for the depth of 400 m or undersized for 800 m. The upper limit of 48 m is based on the rationale that a pillar is non-destructible and can take infinite load due to post-failure strain-hardening behaviour for a w/h ratio of 15 or more. The other approach for chain pillar design includes estimating pillar strength using a pillar strength formula and dividing it by the pillar load determined using numerical modelling procedures to get a Factor of Safety (Ghosh et al., 2020).

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 in these workings. The chain pillars are subjected to non-uniform progressive loading in different stages during their life span. The chain pillars are not reduced in size or extracted, whereas support pillars are extracted during secondary mining. Colwell (1998) observed that the chain pillars designed using the same approach as Bord and Pillar are generally oversized, leading to a significant mineral loss.

Further, an empirical method of the chain pillar design based on the database of the specific condition cannot be used for others unless it is calibrated for the new condition because of the geotechnical and layout differences (Colwell, 1998). With increasing cover depth, the size of the pillar must increase to ensure the safety and stability of the gate entries, which causes a decrease in the overall coal recovery and an increase in per ton mining costs. Large pillars also cause an increase in the cost of ventilation as they offer increased resistance to the airflow. The global trend in longwall design is toward longer and wider panels to minimize the unproductive works associated with the number of face transfers. 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 an adequate safety factor to minimize the pillar size by accurately identifying the loading and strength conditions.

This dissertation provides an approach for the design of chain pillars in deep longwall workings. It is based on the field representative geo-mining conditions of the country with rationally evaluated loading and strength parameters based on the laboratory and field measurements data.

1.1 Objective and Scope

As underground mining is approaching the high-depth coal reserves, the country is currently facing many challenges in designing the longwall panels. One of the challenges is the design of chain pillars to provide serviceable gate roads and adequate ventilation for safe and unhindered production from the longwall face for the life span of the longwall workings. In consideration of these requirements, the objectives of the present work are to:

(a) develop a numerical modelling-based approach for the design of abutment chain pillars for deep longwall workings,

(b) conduct a detailed parametric study to identify the critical factors affecting the failure mechanism and stability of the chain pillars,

(c) establish a safety factor-based criterion for designing abutment chain pillars considering single and double-row layouts in Indian geo-mining conditions, and

(d) evaluate the performance of the approach through a few case studies

The scope of the work is limited to the design of chain pillars with their functional objective of isolation of longwall panels at a cover depth exceeding 360m. The design of the yielding type chain pillar is beyond the scope of this work. This study considers several loading and strength components that can affect the stability of a pillar. The outcomes of this study can save a significant amount of coal without compromising the safety and serviceability of the workings, even in challenging geo-mining conditions.

1.2 Methodology

The methodology used in this study consists of

i. review of pertinent literature for the estimation of chain pillar stability and considerations in chain pillar design,

ii. compilation and analysis of laboratory and field data related to geotechnical, geo-mining, and field experiences for a set of longwall workings in different coal fields in India

iii. 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,

iv. development of three-dimensional numerical modelling procedures to determine the abutment angle formed due to caving of the overlying strata with progressive face advance,

v. development of plain-strain modelling procedures to determine the strength and deformation properties of the damaged overlying strata due to mining and chain pillar stability,

vi. development of modelling procedures for simulating failed and stable coal pillars cases and determining the factor of safety-based criterion for chain pillar stability,

vii. parametric study of factors affecting FoS of the chain pillars and the abutment angle

viii. development of a standard approach for estimating the post-failure softening parameters of the coal pillars and abutment angle,

ix. development of a machine learning-based model to estimate the pillar stability, and

x. verification of the developed approach through case studies.

1.3 Organization of the Thesis

Chapter 1 introduces the present work and establishes its importance in the context of the present and the upcoming scenario of longwall mining in India. It includes the general introduction, definition of the problem, objective and scope of the study, methodology and organization of the thesis.

Chapter 2 outlines the review of literature related to different aspects and the mechanisms of the chain pillar loading and strength. It discusses the globally practised approaches of chain pillar design and their strength and limitations in the context of the Indian geo-mining conditions.

Chapter 3 outlines the formulation and scheme of two-dimensional plain-strain models to evaluate the chain pillar stability. It also presents the formulation and the modelling scheme of the three-dimensional model to estimate the abutment angle under various geo-mining conditions of the longwall workings, laboratory-scale models for simulating the post-failure behaviour of laboratory-scale coal specimen and the constitutive behaviour of gob material.

Chapter 4 provides the numerical modelling-based approach for the simulation of the laboratory observed post-failure mechanical behaviour of coal specimens of varying w/h ratio and the development of a statistical model for estimating the strain-softening parameters for the representative simulation.

Chapter 5 describes the results of the numerical modelling of failed and stable cases of pillars from Indian geo-mining conditions and the development of criteria for the design of chain pillars.

Chapter 6 presents the back-analysis of surface subsidence using numerical modelling and the approach for deriving the strength and deformation parameters of rock mass disturbed under the influence of longwall panels for realistic modelling of the chain pillar behaviour.

Chapter 7 presents the results of three-dimensional numerical modelling to study the effect of various geo-mining parameters on the abutment angle. Based on the outcomes of the numerical models, a statistical model has also been developed to determine the abutment angle in varying geo-mining conditions.

Chapter 8 provides the outcomes of the numerical modelling-based parametric study and the development of machine learning models to design single and double rows chain pillars in different geo-mining conditions.

Chapter 9 presents the implementation of the machine learning model for the rational design of chain pillars in four longwall workings pertaining to different geo-mining conditions in India.

The discussion and conclusions of this work are presented in *Chapter 10,* along with the scope for future work.