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# Design of crown pillar thickness using finite element method and multivariate regression analysis

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ABSTRACT

Minerals are now being extracted from deep mines due to drying up of resource in shallow ground. The need for suitable supports and ground control mechanisms for safe mining necessitates proper pillar design with filling technology. In addition, high horizontal stress may cause collapse of hanging wall and footwall rocks, hence designing of suitable crown pillars is absolutely necessary for imposing overall safety of the stopes. This paper provides a methodology for the evaluation of the required thickness of crown pillars for safe operation at depth ranging from 600 m to 1000 m. Analyses are conducted with the results of 108 non-linear numerical models considering Drucker-Prager material model in plane strain condition. Material properties of ore body rock and thickness of crown pillars are varied and safety factors of pillars estimated. Then, a generalized statistical relationship between the safety factors of crown pillars with the various input parameters is developed. The developed multivariate regression model is utilized for generating design/stability charts of pillars for different geo-mining conditions. These design charts can be used for the design of crown pillar thickness with the depth of the working, taking into account the changes of the rock mass conditions in underground metal mine.


## 1. Introduction

Most of the underground metal mines in India and abroad are being operated at depths beyond 600 m from the surface and some of the mines in India are being planned to mine at even greater depths, beyond 1000 m. The depth of a few mines in South Africa is more than 1000 m. As for example, the Anglogold mine has reached 3700 m, and West Driefovten golden mine arrived at a depth of 6000 m. In addition, in Canada, Australia, United States and other countries, minerals are being mined at a depth over one thousand meters [1]. At greater depth high stress conditions exist and hence, the roof and walls of drives may be damaged due to high convergence and side spalling. Crown pillars are reported to be cracked or damaged due to the excessive load of overlying strata and high horizontal stress. About 43% of the fatalities in South African Gold mines are related to the depths exceeded 2500 m. In those conditions, rock mass are subjected to very high states of rock stress causing seismicity and rock bursting [2]. Accidents due to severe damage in galleries and rock burst induced by deep high-stress conditions have exceeded 40% of the total coal mines accidents in China [3].

The stability of deep high stress rock masses is influenced by many factors, among which the structural characteristics and mechanical states of rock masses are the primary parameters. Stability of structures in deep underground mines can be broadly divided into three different categories; global, regional and local depending on volume of rock involved [4]. The major factors which play important role in pillar stability are: (1) effect of depth of cover; (2) effect of size of excavation; (3) effect of horizontal stresses; (4) effect of rock mass properties; (5) effect of backfilling; (6) effect of reinforcement; and (7) effect of the orebody dipping [5–13].

Although a thick crown pillar provides support for the hanging wall and aid with overall stability of the stopes, but at the same time it may be uneconomical from the mineral conservation point of view. Thus, optimization of pillar dimension is very important for metalliferous mines [14]. Estimation of the optimum thickness of crown pillar is complex, and is generally based on practical experience and various empirical techniques [6,15]. The stability of pillars in deep underground metal mines depends upon the strength or stability of the rock mass surrounding the excavations and upon the stresses induced in this rock. These induced stresses are a function of the shape of the excavations and the in-situ

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stresses which existed before the creation of the excavations. The magnitudes of pre-existing in-situ stresses have been found to be varying widely, depending upon the geological history of the rock mass in which they are measured [16,17].

In India, as well as in abroad, there has been very few works devoted for the comprehensive design of dimension of crown and sill pillars and also to perform stability analysis of the entire stope for deep seated deposits. Existing design methods are limited in scope and the mostly used ones are the empirical techniques or the "rules of thumb" approach. Some researcher suggested a methodology for the evaluation of sinkhole hazard in soft carbonate rocks, combining seismic and mine engineering methods [18]. In the literature it is found that seismic P-wave velocity analysis can be used with a revised relationship that accounts for long-term surface stability of the crown pillar. The empirical analysis on the stability of the crown pillar has been performed considering the crown pillar's thickness and its span as variables of function of its length and width respectively [18]. There is hardly any study devoted for parametric analysis of crown pillar design in cut and fill stopes in deep mining conditions considering several parameters as mentioned above. This study precisely focused on scientific design of horizontal pillars (crown pillars) considering the changing rock mass conditions, variable width of the excavations and increasing depth of the excavations.

The main purpose of this research is to develop a statistical model for the safety factor of crown pillars followed by development of simple design charts which can be used for the design of crown pillar thickness with the depth of the working, taking into account the changes of the rock mass conditions in the studied underground metal mine. The charts is prepared in such a way that it is easy to use for field personnel and contains rock mass conditions, thickness of ore body, thickness of pillars, rock mass properties and depth variables. In this study, numerical analysis are conducted based on parametric study considering a steeply dipping ore body having reducing width with depth of mining (the most common type of orebody shape in India), changing rock mass conditions such as geological strength index (GSI), uniaxial compressive strength (UCS or $\sigma_{ci}$), modulus of elasticity ($E$), and variable thickness of crown pillars. These analyses have been conducted on 108 non-linear numerical models with varying geo-mining conditions with reference to a case study mine located in the eastern part of India. This study develops a generalized statistical relationship (multivariate regression model) between the safety factors of crown pillars with the above mentioned input parameters for further utilization in generating design charts of pillars for different geo-mining conditions.

## 2. Description of the case study mine and models parameters

The ore body of the case study mine has varying dip as well as width as shown in Fig. 1 (transverse section of case study mine). Finite element models of the stopes and pillars are developed below 596 m from the surface at various levels namely 685, 750, 815, and 880 meter level (mL) with a level interval of approximately 65 m. The solid model (Fig. 1), the meshed model with loading conditions (Fig. 2) and the in-situ models are developed considering the actual dip of the ore body, thickness of ore body at different levels and levels at designated depth. Stopes starting from 685 mL, and 750 mL are filled up by mill tailings in the excavated zone in between the in-situ stope pillars (rib pillars) left during the ore extraction. The excavated areas in the stopes starting from 815 mL and 880 mL are completely filled up without leaving rib pillars due to narrow ore body. It is noticed that an excavated height of 4.5 m is left after the last slice below the crown pillar to analyze the worst possible stress conditions in the pillars. In levels 815 mL and 880 mL, post pillars are not needed since width

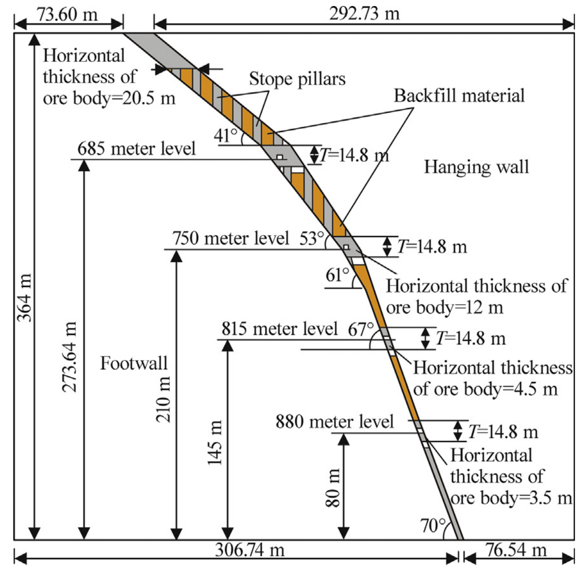


**Fig. 1.** Geometric model of case study mine (transverse section).

of the ore body is less than 8 m as suggested by Directorate General of Mines Safety (DGMS) India. For example, if the thickness of sill and crown pillar is 6 m each, horizontal pillars (Crown of the stopped out area) of 14.8 m (6 × 2 + 2.8) are left considering level drive of height 2.8 m. The general conventions in Indian metal mining industry is that the portion of the horizontal pillar above the level drive is known as sill pillar and the portion of horizontal pillars below the level drive is known as crown pillar [19,20]. Similarly, separate solid models are developed to represent a sill and crown pillar thickness of 4 m, 5 m, and 7 m keeping all other dimensions same. This variation in geometrical model has been done to analyze the stability of crown pillar with variation of other parameters viz. depth of mining, GSI, UCS, and $E$.

## 3. Geotechnical study and rock mass properties of a case study mine

Geotechnical study of the drives, drifts, and pillars has been conducted to determine the condition and spacing of joints so that RMR of hanging wall, footwall and orebody rock mass can be obtained. It may be noted that hanging wall of drives and pillars are cracked and fractured at the deeper level as observed visually in the mine as shown in Fig. 3a and b. These conditions are the evidence of stress concentrations or relaxations around the stopes and pillars.

Geotechnical study shows that the variation of GSI of the orebody rock mass ranges between 42 and 75, uniaxial compressive strength lies between 46.23 MPa and 86.73 MPa, and modulus of rigidity ranges between 9.43 GPa and 16.22 GPa. These data suggest variation in strength properties of the rock mass and hence accordingly this study guides wide range of rock properties as modeling parameters. Three variations of GSI were considered for the study, viz., 50, 60 and 70. Similarly, the uniaxial compressive strength (UCS) of orebody is varied as 50, 65 and 75 MPa, modulus of elasticity of intact rock is varied as 10, 15 and 20 GPa. The strength and modulus of rigidity of rock mass are estimated based on UCS, $E$, GSI and $m_i$ [21,22]. Altogether, 108 finite element models have been developed, based on all possible interactions (namely, modulus of orebody (3) × thickness of sill/crown pillar (4) × RMR/GSI of orebody (3) × uniaxial compressive strength (3)). Apart from this, 27 in-situ or pre-mining finite element models are also developed by varying rock mass parameters. These