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Numerical investigation into the effect of backfilling on coal pillar strength in highwall mining

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ABSTRACT

This paper attempts to quantify the effect of backfilling on pillar strength in highwall mining using numerical modelling. Calibration against the new empirical strength formula for highwall mining was conducted to obtain the material parameters used in the numerical modelling. With the obtained coal strength parameters, three sets of backfill properties were investigated. The results reveal that the behavior of pillars varies with the type and amount of backfill as well as the pillar width to mining height ratio (w/h). In case of cohesive backfill, generally 75% backfill shows a significant increase in peak strength, and the increase in peak strength is more pronounced for the pillars having lower w/h ratios. In case of non-cohesive backfill, the changes in both the peak and residual strengths with up to 92% backfill are negligible while the residual strength constantly increases after reaching the peak strength only when 100% backfill is placed. Based on the modelling results, different backfilling strategies should be considered on a case by case basis depending on the type of backfill available and desired pillar dimension.

1. Introduction

Highwall mining is a mining method that produces coal from the base of highwall in surface mines as illustrated in Fig. 1 [1]. A series of parallel entries are driven into the coal seam using two types of highwall mining systems, namely, continuous highwall mining (CHM) and auger mining. CHM system uses a continuous miner generating typically 3.5 m wide rectangular entries while auger system excavates single or double holes typically from 1.5 m to 1.8 m in diameter [2]. The penetration depths range from 50 m to 500 m depending on the highwall mining systems and mining conditions [3]. The pillars are then left between the mined entries to support the overburden.

Backfilling technology has been widely used in the mining industry. In metalliferous mining, backfilling is typically used to provide a working platform, usually in cut and fill mining, or a support to the pillars and walls for higher productivity [4,5]. It has been widely applied in underground coal mining. In order to reduce surface subsidence, longwall goaf is backfilled to reduce the mining void and subsequently the caving height in some European mines. In Chinese mines backfill material is injected into parting planes in the roof strata to prevent the closure of the partings [6]. In South Africa, backfilling was considered as a way of stabilizing old and/or under-designed bord and pillar workings as well as directly achieving higher recovery by increasing pillar height in thick seam conditions [7,8]. In Australian coal operations, backfilling has not been widely practised though a case of backfilling into pre-driven longwall recovery roadway in weak roof areas in a longwall mine was reported [9]. In another application in Australia, old coal mine workings were backfilled to prevent potential subsidence damage to a new road development on surface [10].

With the wide application of backfilling in the mining industry, research was carried out in the late 1990s to investigate the possibility of utilizing backfilling in highwall mining for the purpose of increasing coal recoveries [5,11]. As illustrated in Fig. 2, a typical highwall mining layout incorporates the web pillars, generated by excavation of a series of entries using CHM system, and the barrier pillars that are left between the panels. If the entries are backfilled, the strength of web pillar will increase due to the confinement. Therefore, with the use of backfill, potentially it may be possible to generate more slender pillars or omit the barrier pillars in highwall mining panel, which can lead an enhanced recovery. In addition, the web pillars are known to fail suddenly accompanying catastrophic domino failures due to their low residual strengths [12,13]. Therefore, apart from the potential advantage of an enhanced coal recovery by using backfilling in

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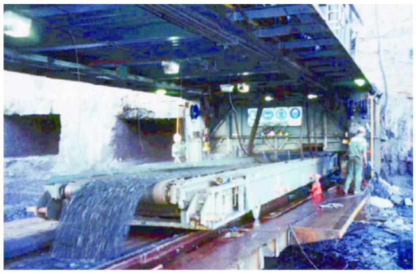

Fig. 1. Highwall mining operation using CHM system [1].

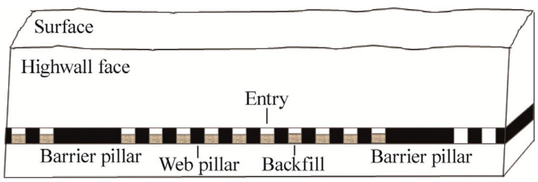

Fig. 2. Typical geometry of highwall mining panel with backfill.

highwall mining, pillar stability will be increased significantly if there is an increase in residual strength with the use of backfill.

A number of forms of backfilling for highwall mining were proposed and relevant filling methods and indicative costs were presented in the past studies [5,11]. Even though backfilling is thought to be effective in increasing coal pillar strength, it was challenging to predict the behavior of the pillars with backfill due to the difficulties in modelling slender coal pillars and the interaction between pillars and different backfill materials.

This paper aims to quantify the effect of backfilling in highwall mining on pillar strength using numerical modelling. While few numerical analyses of the effect of backfilling in highwall mining can be found, a limitation of the studies was the modelling of coal pillars used in highwall mining [11,14]. In this paper, modelling of coal pillars is based on a recent study into a pillar design for highwall mining, which proposes a new empirical pillar strength formula for highwall mining [15]. The numerical investigations into the interaction between the coal pillar and backfill in bord and pillar mining were attempted by Ryder and Wang et al. [7,16], and similar approach is used in this study. In Section 2, coal pillar properties are calibrated to represent the behavior of the slender pillars in highwall mining. In Section 3, different types of backfill are placed into the entry and the strength of coal pillar is monitored with increasing backfill. The significance of the numerical results is discussed in Section 4. It should be noted that only the considerations for CHM system are included in this paper.

2. Calibration of model

Numerical models that are calibrated against empirical pillar strength formulae can be a reliable way to explain the average behavior of a pillar model [17]. In this regard, calibration of coal parameters was conducted against the proposed linear formula for highwall mining recently developed by Canbulat et al. [15]:

$$\sigma_p = 4.66(0.56 + 0.44w/h) \quad (1)$$

where σ_p is the pillar strength, MPa; w/h is the pillar width to mining height ratio.

This new formula has been developed using the maximum likelihood method, which is similar to how the UNSW pillar strength formulae were originally derived [18]. The difference is that only a highwall mining pillar database has been used, which includes a total of 29 cases with 14 collapsed cases and 15 uncollapsed cases. Therefore, it is noted that the formula is only applicable to the highwall mining pillars with width to height ratios (w/h) from 0.5 to 2.5.

It is considered that as the new formula has been developed from an actual database of highwall mining, it represents the best in-situ behavior of coal pillars in highwall mining. Due to the nature of long pillars in highwall mining conditions, plane strain analysis was conducted using the two-dimensional numerical software FLAC [19]. The constitutive law for coal pillars was the strain-softening model based on the Mohr-Coulomb failure criterion. Therefore, the calibration process aimed to back calculate a set of input parameters including the cohesion, angle of internal friction and corresponding plastic strain range.

2.1. Model development

Fig. 3 shows the pillar model incorporating half of coal, roof and floor along the symmetrical centerline of the pillar system which is a repeating geometry in a highwall mining panel. The height of the roof and floor was 20 m and the mining height was fixed at 3 m while the pillar widths varied in order to simulate pillars with w/h ratios from 0.5 to 2.5. The uniform element size of 0.25 m was applied to the coal and a smooth variation of zoning from the coal to the boundaries was used for roof and floor with appropriate aspect ratios to avoid numerical instability. Roller boundaries were applied along the side of the roof and floor, the bottom of the floor and the vertical line.

In this study, the roof and floor were considered to be an elastic material with the stiffer material property [16,20–22]. The interfaces between coal and the roof and floor were taken from recent coal pillar design studies [21,23]. The material properties used for the calibration of model are provided in Table 1.

After generating the grid and assigning the boundary conditions and material properties, the model was stepped to an equilibrium state to develop in-situ stresses. The second equilibrium was then achieved by excavating the entry. The entry width was fixed at 1.75 m which is a half width of a typical entry width of 3.5 m used in the CHM method. Up until this point, very high cohesion and tensile strength values for coal were initially used to minimize the inertial effects so that more static solutions can be obtained.

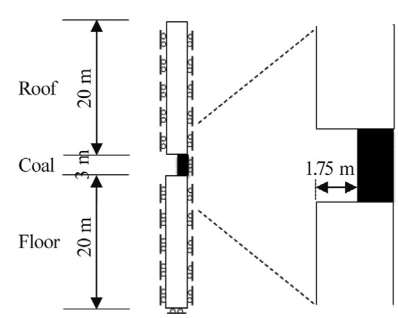

Fig. 3. Geometry of coal pillar model.

Table 1
Material properties used for calibration of model.

Material	Young's modulus (GPa)	Poisson's ratio
Roof/floor	10	0.25
Coal	2.5	0.30
Interface	Normal stiffness = 100 GPa/m; shear stiffness = 50 GPa/m; cohesion = 0.5 MPa; Internal friction angle = 30°	