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A Review of Uncontrolled Pillar Failures

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Abstract

Coal burst is a sudden and violent rock/coal failure that occurs in underground coal mines. It is considered to be a highly catastrophic phenomenon which can cause significant damage to mine workings and equipment as well as result in multiple fatalities. Throughout the history of underground pillar design, the relation between the post-peak behavior of pillars and stiffness of the surrounding strata has been extensively studied. These two concepts play an important role in determining the failure mode of the coal pillars and the amount of potential energy that can be converted to kinetic energy, which is the cause of coal burst. In this paper, the post-peak behavior of pillars and surrounding strata stiffness are reviewed and the criterion developed to investigate the instability of the pillar failures is explained. It is concluded that, as the pillar width to mining height (w/h) ratio increases, its post-peak modulus increases; and a pillar exhibits different failure modes for various w/h ratios.

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Keywords: uncontrolled pillar failure; pillar burst; coal burst

1. Introduction

Experiences in both hard rock and coal mines reveal that pillar failures are still one of the major hazards in underground mining and forecasting the mode of the pillar failure can be vital. Therefore, it is essential to fully understand the mechanics behind these failures in order to predict and control them. As suggested by Tincelin and Sinou [1], pillar failures can be classified into two categories:

i. Slow, progressive deterioration of the pillars that causes relatively delayed surface subsidence and even damage if the pillars fail,
ii. Sudden, violent collapse of pillar causing immediate surface damage and mostly associated with fatal accidents.

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The first type of pillar failures is also named as controlled pillar failures which occur gradually and typically over long periods of time (i.e. pillar spalling). These pillar failures are also termed as creep and squeeze [2]. Uncontrolled pillar failures, on the other hand, take place in a sudden and violent manner and fall into the second group of pillar failures as described above. Since the uncontrolled pillar failures occur rapidly and may not be preceded by any deterioration of the pillars, they cause significant health and safety risks (e.g. coal burst, entrapment, windblast etc.) [2].

Of note is that not all the sudden pillar failures are uncontrolled failures. Particularly in bord and pillar mines, sometimes, controlled and time dependent failures may develop and can reach a level that large scale multiple pillar failure may take place. These are named as 'massive pillar collapses' or 'cascading pillar failures' and may include both controlled and uncontrolled collapses. Such massive pillar collapses are usually associated with undersized pillars with low residual strength values [2–5]. These failures in this mode are usually observable due to high levels of deformations.

It is, therefore, important to gain an improved understanding of mechanics contributing to the uncontrolled pillar failures in order to sustain safe and productive mining practices. In this paper, the two main factors that govern the failure mode of a pillar: post-peak pillar behavior and surrounding strata stiffness, are reviewed and their interactions are discussed. It is also of note that, the principles covered in this paper are applicable for any mining system that involves implementation of coal pillars, whether it is a longwall mine or a bord-and-pillar mine.

2. Effect of pillar geometry on post-peak behavior

The performance of a pillar is controlled by a number of factors, including the inherent strength of coal, cleating, fracturing, internal friction angle, cohesion, surrounding strata conditions, pillar geometry and roof/pillar/floor contact conditions [6]. Additionally, due to the variation in geological and geotechnical conditions as well as mining methods, the size and shape of the pillars are modified accordingly and can show drastic differences. For instance, rectangular pillars normally have somewhat higher strength due to the increased confinement; length–to–width ratio of 2, 3 and 4 can result in the increase of the pillar strength by 1.1, 1.2 and 1.3 respectively [7].

The variety in the pillar geometries, mainly in w/h ratios, may also change the mode of pillar failure. According to Salamon [8], while pillars with intermediate w/h ratios ($3 < w/h < 5–7$) can fail suddenly and violently as a whole, wide pillars ($w/h > 7$) would only suffer from side failures and pressure bursts but complete pillar failure would not occur. This agrees with the experiences in Germany where coal bursts (possibly rib bursts) are observed only in the pillars with w/h ratios between 8 to 20 [9]. However, as it was reported by Gates et al. [10] that in the tragic Crandall Canyon Disaster (2007), pillars with w/h ratios up to 8 had completely failed within a few seconds over a distance of 800 m. Therefore, it is reasonable to assume that the sudden failures of coal pillars are usually determined by the loading mechanisms; if the pillars are subjected to high levels of loads, sudden failures are possible even with large w/h ratios.

Mark [4] has also classified the pillar failure modes based on their w/h ratios. In his paper, three categories of pillars are noted: slender pillars ($w/h < 3$); intermediate pillars ($4 < w/h < 8$) and squat pillars ($w/h > 10$). Mark stated that slender pillars can experience sudden collapses due to their low residual strength values while intermediate pillars are commonly squeezed slowly by the surrounding strata; squat pillars, however, can carry extreme loads and are associated with pressure bursts and rib failures. Mark's categorization partially complies with observations of Gates et al. [10].

Researchers have conducted laboratory [11, 12] and in-situ tests [13–20] to investigate the effect of w/h ratio on the pillar strength and post-peak behaviour. Das [11] carried out several laboratory tests to obtain full stress-strain curves of specimens within a wide range of w/h ratios (0.5–13.5). He showed that peak and residual strength of the material as well as its post-peak modulus varies as the w/h ratio changes. He also reported that at low w/h ratios, specimens show strain-softening behaviour hence the stress-strain curve slopes downward in the post-peak region. Furthermore, around the w/h ratio of 8, specimens exhibit elastic-plastic behaviour and their modulus converges to zero. If the w/h ratio continues to increase, they show strain-hardening behaviour and gain a post-peak modulus greater than zero. However, many cases of pillar failures have shown that there is no correlation between the laboratory tested UCS and the actual pillar strength [4].

Empirical formulas have also been developed to calculate the post-peak stiffness of the full-scale pillars by back-analysing the in-situ pillar tests: