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An improved method for long-term stability evaluation of strip mining and pillar design

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1. Introduction

Strip mining method is often the preferred way to extract the coal reserve under important surface structures and water bodies in China.[1,2] Fig. 1 shows a typical layout of a strip mining mine. The main advantage of employing strip mining is that it can prevent the mining-induced strata movements from propagating to ground surface so that significant mining disturbances to surface structures can be avoided.[3,4] Long-term stability of strip pillars is required to protect surface structures and water bodies. However, the existing pillar design method rarely considers the long-term behaviors of coal pillars. For example, the weathering effect can slowly degrade the coal pillar and reduce the size and stability of the coal pillars. This could lead to the failure of some of the originally stable pillars and subsequently unexpected surface subsidence. As more and more coal mines are closed, such progressive pillar failure becomes a significant cause for unexpected subsidence and structural damages in mining area. Therefore, research efforts should be made to study the long-term stability of strip pillar and to develop a systematic design method for strip mining operations.

The long-term stability of mine pillars has been studied by many researchers.[5–10] The combined effect of weathering and stress can cause progressive pillar size reduction due to peeling (or spalling) of pillar ribs and weakening of mine pillars. Such progressive pillar failure is termed as pillar peeling. The pillar peeling rate (or pillar deterioration rate) was studied by Merwe[7,8] and Salmi et al.[10] A constant pillar peeling rate was adopted to predict the pillar life. However, there are three shortcomings in present long-term pillar stability evaluations: (1) Because of the complicated coupling-effect of stress and weathering, the assumed constant pillar peeling rate is empirical and site-specific and difficult to get a reasonable evaluation result that matches with reality; (2) a pillar is assumed to be peeled in an unlimited deterioration process leading to the conclusion that no pillar will be stable eventually; and (3) without considering the coal debris peeled from pillar rib and the confining effects of these coal debris.

The weathering factors affecting pillar strength and size reductions are mine water, humidity, coal oxidation, etc.[10] Fig. 2 shows some engineering cases of distribution of coal debris and coal pillars.[11] It is well recognized that the coal debris peeled from the pillar rib that piled around the coal pillars can provide horizontal confinements to the pillars. Thus, the coal debris pile may prevent the pillar ribs from further deterioration. Salamon et al. considered the property of peeled coal debris and proposed a pillar peeling model in which the ultimate size of the weathered pillar can be calculated.[9] Yu et al. advanced and analyzed the pillar peeling model for room-and-pillar mines,[12] but his method is not suitable for strip mining mines.

To ensure the long-term safety of mines and ground structures, the underground pillars should have the ability to resist the effect of pillar size reduction. In this paper, we consider the progressive pillar size reduction and the confining behaviors of the peeled coal debris and propose a new pillar peeling model for long-term stability design of the strip pillar. The model represents the worst case scenario of a pillar, and the limit of pillar peeling can be determined.

2. Pillar peeling model for strip mining

The strip mining is not only suitable for shallow mining but also suitable for mining at deep depth. The strip pillar is different to the pillars in classical room-and-pillar mines. The pillar width and mining width are usually large enough in strip mining, and the pillar rib usually yields due to the large mining width and the large mining depth. Thus, the pillar can be seen as having two parts: an elastic core and a surrounding plastic yield zone (Fig. 3a).

For a mine pillar, its rib will peel under the influences of weathering and stress. Studies indicated that the coal peeling is more likely to occur at the upper part of the pillar than its lower part.[11–16] On the other hand, with the height of peeled coal debris pile gradually increases during pillar peeling, the bottom part of the pillar will be the first part that covered and restrained by the coal debris, it is very possible that the pillar peeling is more severe at pillar top. Therefore, the maximum peeling depth may be underestimated if a uniform peeling progress is assumed, it is more reasonable and safer to assume a non-uniform pillar peeling model. In this study, a quarter of an ellipsoid is used to

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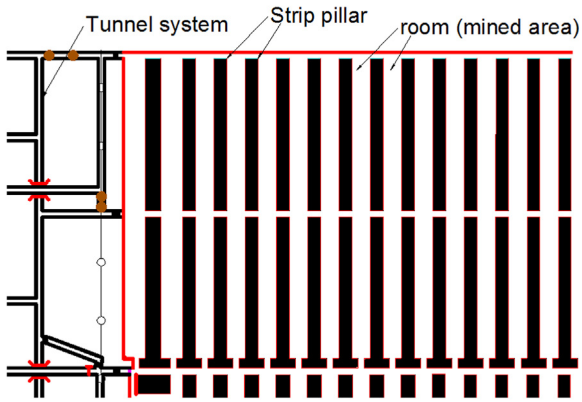

Fig. 1. Layout example of a strip mining mine.

represent the peeling areas on a pillar as shown in Fig. 3. The major axis represents the pillar height and the minor axis represents the maximum peeling depth on a pillar. When a portion of the pillar is buried by the peeled coal debris, the coal will not peel because the weathering effect will no longer affect that part of the pillar rib and the pillar rib is restrained by the coal debris. When the height of the coal debris pile equal to pillar height and the pile reaches the repose angle, the whole pillar will be covered and restrained by a stable pile. Therefore, the pillar size reduction will stop if the pillar rib is surrounded by a coal debris pile.

Depending on the mining width, there are two possible types of debris piles. When the mining width is large and the two coal debris piles from the facing ribs do not overlap, the pillar is called an "isolated" pillar as shown in Fig. 3b. For small mining widths, the debris piles overlap and the pillar is called a "non-isolated" pillar (as shown in Fig. 3c). The minimum mining width leading to an "isolated" pillar is defined as the critical mining width (w_{CD}).

In the model development, the initial pillar width is w_p, the minimum pillar width (width of pillar top) after pillar peeling is w_p'', the maximum peeling depth on a single side of a pillar is d_m; the width of combination of residual pillar and peeled coal debris pile (base width of the trapezium) is w_p'; the pillar height is h. The following equations can be derived based on Fig. 3:

$$w_p'' = w_p - 2d_m \tag{1}$$

$$w_p' = 2fh + w_p - 2d_m \tag{2}$$

$$f = \frac{1}{tan\theta} \tag{3}$$

where θ is the repose angle of peeled coal debris pile, °.

Since the length of strip pillar is significantly longer than the pillar width, the effect of pillar peeling in pillar length direction can be ignored. For a unit length of the strip pillar, the peeled coal will expand with a bulking factor k. The total volume of peeled coal debris pile can be calculated as:

$$kV_{peel} = V_T - V_{Res} \tag{4}$$

where V_{peel} is the peeling volume of coal pillar; V_{Res} is the residual pillar volume; V_T is the total volume of residual pillars and coal debris pile.

The volumes of peeling area V_{peel} and residual pillar V_{Res} are determined by:

$$V_{peel} = 2\times\frac{hd_m}{4} = \frac{\pi}{2}hd_m \tag{5}$$

$$V_{Res} = w_p h - V_{peel} = w_p h - \frac{\pi}{2}hd_m \tag{6}$$

V_T for an "isolated" pillar is (Fig. 3b):

$$V_T = \frac{1}{2}(w_p'' + w_p')h = fh^2 + w_p h - 2hd_m \tag{7}$$

Combining Eqs. (1) and (7), the maximum peeling depth on pillar after peeling progress stops is estimated as:

$$d_m = \frac{2fh}{4+\pi(k-1)} \tag{8}$$

The critical mining width w_{CD} that leads to an "isolated" pillar (Fig. 3b) is:

$$w_{CD} = 2fh - 2d_m = 2fh(1 - \frac{2}{4+\pi(k-1)}) \tag{9}$$

When the mining width w_c is smaller than w_{CD}, V_T for "non-isolated" pillars can be calculated by:

$$V_T = (w_p + w_c)h - h_1\left(d_m + \frac{w_c}{2}\right) = (w_p + w_c)h - \frac{1}{f}\left(d_m^2 + w_c d_m + \frac{w_c^2}{4}\right) \tag{10}$$

$$h_1 = \frac{1}{f}\left(d_m + \frac{w_c}{2}\right) \tag{11}$$

By combining Eqs. (1)–(6), (10) and (11), the maximum peeling depth for "non-isolated" pillars depends on the mining width w_c and is determined as:

$$d_m = -\frac{w_c}{2} - \frac{\pi(k-1)fh}{4} + \sqrt{\left[\frac{\pi(k-1)fh}{4}\right]^2 + fhw_c\left[1+\frac{\pi(k-1)}{4}\right]} \tag{12}$$

The maximum peeling depth on pillar after pillar peeling stops can be determined by both Eqs. (8) and (12). The maximum peeling depth on the pillar are affected by the pillar height, repose angle of coal material, bulk factor of coal and the mining width.

The bulk factor of coal is usually 1.05–1.35,[12,17] and the repose angle of coal is usually $27° - 45°$[12]. The critical mining width w_{CD} for different pillars are shown in Fig. 4. The w_{CD} increases with the increase of θ and h. As the mining width of strip mining is usually larger than 20 m, most strip pillars are "isolated" pillars.

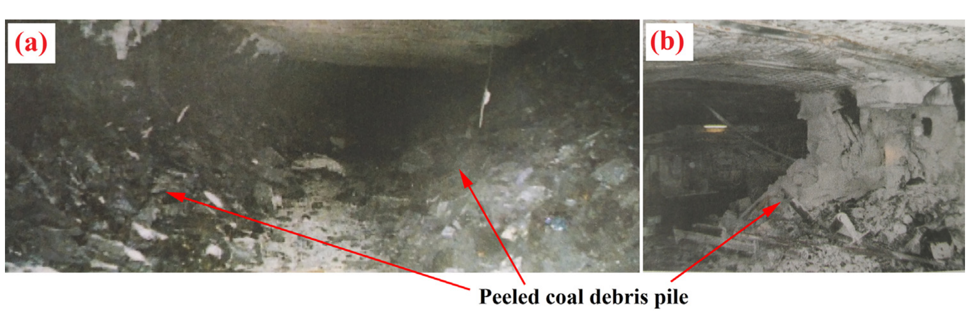

Fig. 2. The distribution of peeled coal debris piles in coal mines, U.S.[11]: (a) peeled coal debris piled around pillar in Hiawatha 2 seam; (b) peeled coal debris piled around pillar in Hiawatha 1 seam.