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Technical note

Numerical investigation of coal pillar failure under simultaneous static and dynamic loading

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1. Introduction

Coal pillars perform a number of different functions including protection of gate roadways or entries, panel isolation to guard against spontaneous heating, protection of mine shafts, and avoiding surface subsidence.[1] Coal pillar failure often poses significant safety issues and occasionally puts lives at risk. For these reasons, a significant amount of research on pillar strength and design has been conducted in the past few decades. Salamon was the first author to propose an empirical and semi-statistical approach for pillar strength calculation from work on South African coal mines in the 1960s.[2] In this paper, the numerical investigation of pillars under simultaneous static and dynamic loading in a coal mine in China was conducted.

From a design perspective, pillar width-to-height (W/H) ratio is an important number because it relates to both the amount of the coal resource that can be recovered and coal pillar stability. The failure behavior of a coal pillar is affected by the W/H ratio and laboratory tests and numerical simulation have observed that pillars exhibit strain-softening when the W/H ratios are small. However, for large W/H ratios, the pillars become strain hardened.[3] To design practical coal pillars, some researchers have investigated the effect of pillar size. Bieniawski established an empirical size for pillars.[4,5] Van Heerden and Maleki conducted extensive field tests on coal pillars of different W/H ratios to estimate stress–strain behavior.[6,7] Carr et al. published the measured vertical stress distribution within different sized pillars after entry development.[8] Li and Bai attempted to propose a new approach for yield pillar design based on field measurements, case studies, and numerical modeling for back analysis.[9] All these studies were based on coal pillars under static loading conditions but none considered the effects of dynamic loading. However, with changing mining practices, an increasing number of coal pillars are subjected to static and dynamic loading simultaneously. For example, simultaneous loading will occur when the mine plan involves driving a gob-side entry heading adjacent to an advancing working face (HAWF). That is the case considered in this paper. Few integrated studies on coal pillars and dynamic loading have been published. Rajendra Singh et al.[10] presented a method for assessing dynamic loading of pillars during caving of the roof strata, but the size of the coal pillars and the failure mechanisms were not studied. Previous research in China has defined the changes in abutment pressure under dynamic loading by numerical simulations,[11,12] but these studies are not entirely relevant because the effect of dynamic loading was inconspicuous. In this paper, dynamic loading is defined as simple harmonic waves caused by roof caving.

Understanding coal pillar failure mechanisms and dynamic response under static and dynamic loading is necessary to ensure

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that a pillar has an appropriate *W*/*H* ratio. This paper attempts to propose an approach for simulating static and dynamic behavior of coal pillars using FLAC^{3D} software, and examine the mechanisms involved in pillar failure as well as investigating the pillar's dynamic response.

2. Pillar failure characteristics

In the traditional mining excavation method known as gob-side entry driving, the drive is done along the edge of stable gob.[13] If this method is used, it is hard to prepare the next panel for production before the current panel is mined out. To solve this problem, a new method for laying out longwall panels was developed called gob-side entry driving heading adjacent to the advancing working face (HAWF).[14] However, because of the dynamic and varied stresses generated during excavation, new engineering problems have emerged such as finding a reliable design for the coal pillars.

To investigate pillar failures during the different phases of HAWF gob-side entry driving, we used FLAC^{3D} numerical analysis software to simulate the four stages of entry driving (Stages I, II, III, and IV in Fig. 1).

It should be pointed out that both mining and movement of the strata can generate dynamic loading. This loading can come from mechanical vibration, blasting, strata caving, fault slip, and other causes.[15,16] In this case study, the caving of a roof layer is the main source of dynamic loading during the HAWF gob-side entry driving. The four stages of HAWF are illustrated in Fig. 1.

Stage I: entry driving in coal mass. Under only original ground stresses, coal pillars are easy to maintain.

Stage II: entry driving under advancing abutment pressure. In this stage, the coal pillar is affected by pressure from the abutment of the adjacent working face and the vertical stress on the coal pillar increases gradually as the working face advances.

Stage III: entry driving under static and dynamic loading. In this stage, entry driving meets the panel #1 longwall retreating face (Fig. 1) and roof control is very difficult. A schematic diagram of roof caving is shown in Fig. 2.

The caving of a massive and strong roof produces two types of dynamic loads. First, elastic energy release when the roof caves causes mine seismicity and the coal pillar experiences a dynamic load when the seismic wave acts on it. Second, the caving of a massive and strong roof is sudden and the deflection of the roof (the reduction of the potential gravitational energy) suddenly generates a dynamic load at the moment of caving.

Based on mechanical relationships and conservation of energy, seismic energy E_s, caused by roof caving, can be expressed as:

$$E_s = E_l + E_g - E_s - E_j - E_c \quad (1)$$

where E_s is the seismic energy released by roof caving; E_l is the work done by the upper load on the roof; E_g is the work done by gravity when the roof caves; E_s is the energy consumed by the roof's plastic deformation; E_j the energy consumed by shearing

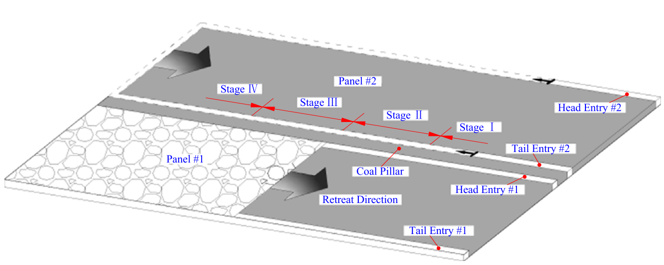

Fig. 1. Position of HAWF gob-side entry driving.

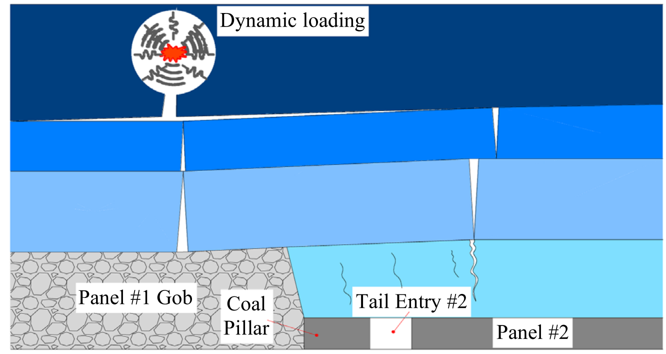

Fig. 2. Schematic diagram of roof caving.

displacement of the joints in the roof; E_c is the residual strain energy in the roof after caving.

The pillar may be badly damaged under the combined static and dynamic loads at this stage. To analyze the pillar failure, Stage III can be divided into two parts, a static load that is induced by roof bending subsidence and a dynamic load induced by the sudden caving of a massive and strong roof.

Stage IV: entry driving along stable gob. This drive is influenced only by pressure from the stable lateral abutment of the adjacent gob; the coal pillar is located in a low stress area.

3. Geological background and site details

The Qipanjing Coal Mine in Ordos, China, was selected for this case study. The longwall panels selected for this study were the 0912 and 0913 panels; both were mined to extract coal from the No. 9 seam. The panels were 200 m wide and 1100 m long and developed by the single-entry system with an entry 3 m high and 5 m wide. Typically, longwall panels in China employ the single-entry system with only one coal sill pillar left between adjacent panels. The coal seam was 3 m thick and the overburden averaged 350 m. Rock layers above the coal seam, from the seam up, were mudstone, sandy mudstone, mudstone, fine sandstone, and sandy mudstone. Below the coal seam, from the seam down, the floor consisted of sandy mudstone followed by the #10 coal seam, sandy mudstone, the #11 coal seam, and lastly fine sandstone.

After the 0912 panel was mined out, the 0913 tail entry and head entry were driven to develop the 0913 longwall panel. The coal pillar between the 0912 and 0913 panels is 6 m wide by 3 m high, resulting in a *W*/*H* ratio of 2. Field observations showed that, at Stage III, the damage to the coal pillar was quite serious and the entry convergence was large (blue rectangle in Fig. 3). There were obvious protuberances on the surface of the coal pillar (Fig. 3a), and the hydraulic props were punched into the floor (Fig. 3b). Nevertheless, the coal pillar retained a considerable load-bearing capacity and remained stable.

4. Numerical modeling

4.1. Global model and simulation plans

The numerical model had two parts, static analysis and dynamic analysis. The method of modeling consisted of the following steps:

Grid generation. Numerical distortion of the propagating wave can occur in a dynamic analysis as a function of the modeling conditions. For accurate representation of wave transmission through a model, the spatial element size, Δl, must be smaller than