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Study on mechanics and domino effect of large-scale goaf cave-in ☆

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ABSTRACT

A large area of continuous solid shallow-buried goaf group created by open-stope method, under the influence of space–time effects exerted by slow creep of the pillar–roof system, will wholly collapse driven by partly instability of pillar and roof collapse until the whole mine collapses, showing a domino effect. The dynamic process is ignored in the traditional analysis of mechanical stability. Based on analysis for the domino effect and disaster-relief mechanism in the mining goaf, the mechanical method combined with Voronoi graph method has been adopted to establish the dynamic analysis on the pillar–roof system stability. It seems more in line with the actual situations, and can help to more accurately predict the time and location of disaster. The conclusion is of great value on study of rock mechanics and mining companies' safety production.

1. Introduction

The goaf refers to the interconnected continuous space after the underground ore has been mined, while the goaf group refers to the densely distributed interconnected continuous spaces, jointly leading to the rock movement or caving. It usually refers to a large number of goafs combined in a mine field. When the goaf of the mined area reaches a certain size or is damaged by the slow creep in the surrounding rock, the roof and the pillar cannot support the upper overburden load. As a result, the surface subsidence, building collapse and shock waves in the underground will take place to endanger miners' lives. The disasters in goafs are the most dangerous mining disaster (Haitao et al., 2009) in terms of its distribution and frequency. 70–80% of China's metal mining disasters have happened in goafs (Qiming, 2005). The subsidence area caused by mining has reached 1150 km^2. It has been identified in more than 30 cities each year due to ground subsidence. 400 million Yuan (Qian et al., 2004) has been lost in this regard.

From the theoretical point of view to study the mechanical failure mechanism of the roof, it will help us to understand the mine pressure transient nature of mines in a deeper level. The engineering control problems for roof cave-in can be solved. It will be very positive for mine safety and social harmonious development.

2. Gob domino effect of instability in goaf

2.1. Failure modes in goafs

62.5% of China's metallurgical mines, 89% of non-ferrous metal mines and almost all gold mines are mined underground, and the open-stope method has been adopted in about 53.5% of them. The goafs created by the open-stope method feature more solid surrounding rocks, larger exposed areas and great volume. Once the bulky goaf group has been formed, it will help to accumulate a large number of elastic potential energy, which will be the main sources for risky disaster. The failure modes in goafs can be broadly grouped into three types like strip-type, room–pillar type, lane–column type and knife–mining type.

- First point, partial damage of caving arch in the rock arch of pillar and mine roof plate (Fig. 1a). This damage will occur when the balanced arch structure will be formed between the undamaged pillars. Due to local stress concentration or tectonic action, the roof section will collapse so that the shock wave in smaller area will come into being. The air can keep stable because the cracks are not connected with the surface.

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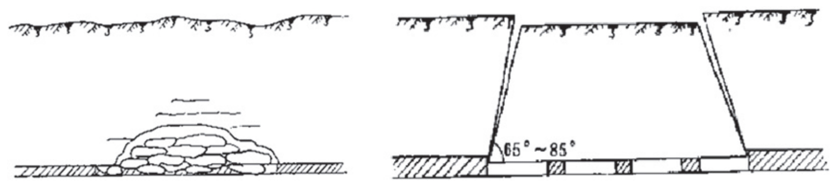

Fig. 1. Caving-type diagram for gob roof.

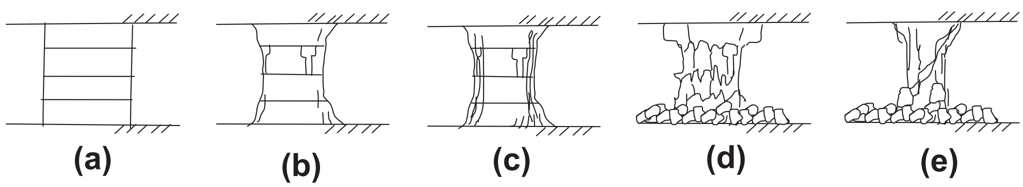

Fig. 2. Caving-type diagram for gob roof.

- Second point, local pillars remain instable while the roof remains stable (Fig. 2). It usually happens when the ore body is relatively soft and the roof strata are relatively solid. For the load of the mine pillars exceed their own limits, the pillar will collapse. However, a large area cannot fall down but remain flexible. It will help to create a large and stable hanging roof.
- And so on, pillars remain instable and while the roof strata is damaged. A large area of the surface collapses instantaneously (Fig. 1b). When pillars collapse, the stress will be transferred to the surrounding pillars. The damages will spread from the roof strata to the earth surface layer by layer so that it will fall down. Without the pillars' supporting, the goaf will come into being, posing great geological disasters for ground movement.

2.2. Domino effect of gob caving

All kinds of damages in goafs are interrelated and mutual transformable in terms of time and space. When the gob occurs at the very beginning, part of roof will fall down under the influence of rock structure, joints, cracks and local stress. Then a natural balance of the arch will be formed and it will remain stable in the long run. Under the impact of the roof load, the ore pillars will creep slowly. When the creep spread to the core supporting area, the ore pillars will become unstable and no longer bear any load. After losing the support of the lower part of the roof, the partial caving will fall down. Then the new stress arch will be formed and the load will be transferred to the surrounding pillars. After the load on the surrounding pillar gets increased, the instability may be further increased. Therefore, the stress of the roof will be transferred outward. Finally, after stress arch fractured zone reaches the surface, a large area of surface will instantaneously collapse when a number of pillars' instability occurs and they cannot support the upper strata load. The load transfer and chain-type damage of roof pillar induced by the partial destruction on pillar will eventually lead to the large-scale collapse. The phenomenon is known as the "domino" effect in goaf as shown in Fig. 3.

This type of accidents created by open-stope method in mined-out area has occurred from time to time, causing serious mass injuries and death, serious surface subsidence as well as all-mine devastation. On June 9, 1986, an area of 800 square meters of Beicun Coal Mine, located in the southern suburbs of Datong Mining Bureau fell down. Then, a larger area of 89,425 square meters of Beicun Coal Mine, Xiaonantou Coal Mine, Jiucaigou Coal Mine and the Coal Mine affiliated to 51,056 Army suddenly collapsed. On June 13, another 80,500 square meters area fell down, causing very heavy losses. On November 6, 2005, Kangli Gypsum Mine in Xingtai City in Hebei Province collapsed, then it spread to Taihang Gypsum Mine and Linwang Gypsum Mine where an area of 480,000 square meters collapsed and some houses also collapsed, claiming a total of 33 lives (Haitao, 2007). The mines that have experienced the instability brought by "domino" effect in large area of goaf will have the following three common characteristics: (1) When the goaf rate is greater than 60%, the pillars will bear greater load and a large area of roof will be exposed; (2) when the ratio of coal pillars' width to height is generally less than 3, or when the ratio of metal pillars' width to height is generally less than one or when the ratio of non-metal pillars'; width to height is generally less than two, the residual stress is smaller after the pillars have been damaged. (3) When the depth of the mined areas is very shallow, the cracks will spread to the surface.

Based on a large number of actual accidents, there are four main factors contributing to the domino effect in goaf: (1) Due to great stiffness, the roof can withstand a greater load and can host a lot of deformation energy; (2) due to the low carrying capacity of local pillars or large exposed area in goaf, the bearing capacity of the pillars will reach to the limit; (3) due to the low carrying capacity of pillars, most pillars cannot afford any additional stress after the transfer; (4) With no safe isolation pillars or deficient bearing capacity of pillars, the stress cannot be prevented from passing by.

Therefore, the mechanical analysis and disaster risk assessment methods for the goaf should be further studied from the mechanical process of goaf group composed by pillars and roof.

3. Pillars and instability analysis for pillar groups

3.1. Instability factors of pillars

The following factors may affect pillars' stability: the bearing capacity of the pillars, the ratio of pillars' width to height, pillar location and distribution, tectonic factors and rock strength. According to the results from the test, the greater ratio of pillars' width to height is, the higher pillars' strength is. Generally speaking, the ratio of pillars' width to height has become the main indicator for pillar design. According to the ratio (w/h) of pillars' width to height, it can be divided into: slender pillars ($w/h < 4$), the crude pillars ($4 \leqslant w/h < 10$) and pier-shaped pillars ($10 \leqslant w/h$). Pier-shaped pillars can withstand considerable loads, or can even keep unchanged or "indestructible" when bear greater loads as shown in