Journal of Rock Mechanics and Geotechnical Engineering 8 (2016) 886–895

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Failure of hanging roofs in sublevel caving by shock collision and stress superposition

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ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form
25 May 2016
Accepted 22 June 2016
Available online 17 September 2016

Keywords:
Shock wave collision
Hanging roof
Sublevel caving
Rock fracture
Hang-up
Underground mining

ABSTRACT

Hanging roofs or high hang-ups, a common problem in sublevel caving mining, usually result in a large ore loss and undermine mining safety. This paper analyzed the formation of a hanging roof and showed that increased confining pressure and reduced free surface were its main characteristics. In order to break down a hanging roof, a new method based on shock wave collision and stress superposition was developed. In this method, two blastholes containing multi-primer at different positions are simultaneously initiated at first. By doing this, a new free surface and a swell room can be created. After these holes are fired, a long delay time is given to the next blasthole so that the fragments from the first two-hole blasting have enough time to fall down. This new method was applied to three hanging roofs in one production area, and all of them were successfully broken down. Field inspection indicated that almost no damage was caused in the nearby drifts/tunnels due to the new method. In addition, the far field vibrations were found to be smaller than the maximum vibrations induced by some other blasts.

1. Introduction

The modern sublevel caving, possibly developed in the iron mines of Sweden (Hustrulid and Kvapil, 2008), is a widely used mining method in metallic mines across the world. This method has many advantages regarding safety and mechanisation (Janelid and Kvapil, 1966). Because mining operation is carried out only in drifts, the safety of this method is relatively good, compared with other mining methods such as cut-and-fill, and room and pillar. However, sublevel caving has two main disadvantages: high ore loss and high dilution. Therefore, how to reduce ore loss is an important task for sublevel caving.

Investigations including Janelid (1968), Kvapil (1982), Ren (1994), Stazhevskii (1996), Hustrulid (2000), Rustan (2000), Quinteiro et al. (2001a), Power (2004), Selldén and Pierce (2004), Zhang (2005, 2014a,b, 2016), Brunton et al. (2010), Wimmer (2010), Tawadrous (2015), and Nordqvist and Wimmer (2016) have indicated that rock blasting has a great impact on fragmentation and recovery. Furthermore, there is a great potential to increase ore recovery by improving blasting (Zhang, 2016). At the same time, unfortunately, there exist various problems in present underground blasting. One of such problems is the hanging roof in sublevel caving.

In a normal condition, after a sublevel ring is blasted, the ore mass in the ring is completely destroyed into various sizes of fragments, and a new front face is formed. When ore extraction in the ring is completed, the new front face is partly occupied by the waste rocks (or mixed with ores). As a result, a large number of waste rocks move down to the drift floor and waste-rock boulders often partly block the draw point, as shown in Fig. 1a. However, sometimes, after a ring is blasted, the upper part of ore mass in the ring is either poorly fragmented or seriously confined. Under this circumstance, when extraction in the ring is finished or it cannot continue, the upper part of ore mass is hanged there and an empty room is formed below the upper part, as shown in Fig. 1b. This hanged part of ore mass is called hanging roof, also called "remained roof" or "high hang-up" (Hustrulid and Kvapil, 2008), which is similar to but not same as an ordinary hang-up in caving mining. An ordinary hang-up frequently happens in block caving and sublevel caving, and it may break up by itself during extraction. Different from an ordinary hang-up, a hanging roof does not break up by itself. A hanging roof is common and it results in a large ore loss in sublevel caving. As reported by Zhang and Naarttijavi (2006), the ore loss due to hanging roofs was up to 380,000 t in Malmberget mine during two-year production. In addition, a hanging

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2016.06.005

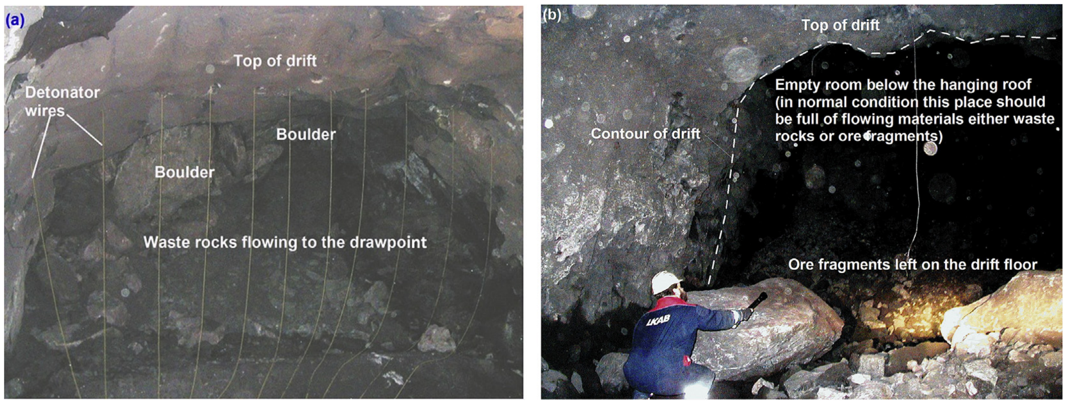

Fig. 1. The draw points in a normal condition and a hanging roof condition. (a) The draw point picture in a normal condition taken from the drift floor on which the waste rocks rest; (b) the draw point picture in a hanging roof condition.

roof may bring about a potential risk for the people working underground because it may come down with an air shock at any time. Therefore, techniques for breaking down a hanging roof are needed.

In the Malmberget mine, one method was often used to handle hanging roofs (Zhang and Naarttijavi, 2006). This method is called old method in this paper and it is illustrated in Fig. 2. As shown in Fig. 2, a hanging roof is formed, starting from ring 1 (R1). After R1 is blasted, its upper part remains. Then when extraction in R1 is finished, R2 is blasted as usual. As this process continues, more and more rings are blasted and the hanging roof becomes larger and thicker. After R12 is blasted, most of the ore mass in the ring is hanged. In order to keep a stable mining production and assure a safe work condition, several rings behind R12 have to be left without blasting so that a new opening slot, as indicated in R17, is made. This method can sustain mining production, but the ore within several rings (e.g. R12-R16 in Fig. 2) has to be left as a permanent ore loss since no blasting is involved. In order to reduce such ore loss due to the old method, it is necessary to develop a better method.

This paper will introduce a new method for breaking down hanging roofs. This new method was conceptually mentioned earlier (Zhang and Naarttijavi, 2006) but sufficient analysis was lacking. In this paper, the formation and characteristics of hanging roofs will be described. Then the principles of the new method will be introduced. Finally, the applications of the new method to three hanging roofs will be in detail reported.

2. Formation and characteristics of hanging roofs

2.1. Formation of a hanging roof

The Malmberget mine is a large apatite-iron ore deposit, consisting of 20 ore bodies containing both magnetite and hematite. The iron content varies from 54% to 63%. The uniaxial compressive strength of the ore ranges from 85 MPa to 140 MPa. The country rocks consist of metamorphosed volcanic rocks such as gneisses and fine-grained feldspar-quartz rocks called leptites. The uniaxial compressive strength of the red leptite varies from 170 MPa to 220 MPa, and that of gray leptite ranges from 70 MPa to 160 MPa. Over the entire ore field, one structural group strikes and dips subparallel to the ore bodies (Quinteiro et al., 2001b).

The mining method is sublevel caving with a sublevel height varying from 20 m to 30 m. The production blastholes are 115 mm in diameter, each hole contains one primer, the dirft is 7 m wide and 5.5 m high, the explosive is emulsion with a VOD (velocity of detonation) of 5000 m/s (Nordqvist and Wimmer, 2014), the delay time between holes is 100 ms, and the P-wave velocity of the rock/ore mass is about 5100 m/s (Zhang, 2014c).

In the mine, a hanging roof may occur in either a large ore body or a very narrow ore body. In both ore bodies, hanging roofs can be divided into two types. The first type, often found in narrow ore bodies and shown in Fig. 2, occurs from the first production rings in a sublevel drift. A major reason for this type is an unsuccessful open cut, i.e. the blast surrounding the opening slot in the beginning of a drift does not create an opening large and high enough for the next blasting. An unsuccessful open cut can be caused by various reasons, one of which is that the slot is too short to reach the top of the ring. For example, as shown in Fig. 2, the slot (the slot is not shown but it is assumed that the top of the slot is at the position S_E) just reaches the position S_E in front of the first ring, R1. In this case, when open cut is made, a certain upper part (roof) of R1 will be left as shown in Fig. 2a. As soon as the roof of R1 is remained, it is easy to form a thicker hanging roof in R2 if it is blasted as usual. If R3 and other following rings are blasted one by one as usual, the hanging roof will become thicker and larger. As indicated in Fig. 2a, the roofs of R1 to R11 are all remained.

The second type of hanging roofs appears due to unsuccessful blasting in several neighboring rings. This type is shown in Fig. 3. Different from the first type, the second type has a partly free surface, which is parallel to the ring plane but is at least two burdens far from the ring to be blasted, as shown in Fig. 3a. In addition, the second type does not happen in the beginning of drift. Similar to the situation in the first type, when a ring is not well blasted and its roof is remained, if the next ring is blasted as usual, then the hanging roof becomes thicker and larger. Under this circumstance, if the next following ring is still blasted as usual, the hanging roof will become much thicker until the last ring cannot be well blasted at all. For example, R13 in Fig. 3 cannot be destroyed as usual after the roof of R12 is remained.

2.2. Characteristics of a hanging roof

2.2.1. Stress state

For an ordinary ring to be blasted, its front face is partly covered by the waste rocks with different sizes. For example, in Fig. 3 the boundary between the front face of R8 (one ordinary ring) and the caved waste rocks is a partly free surface, meaning that the horizontal stress, along *X*-direction, applied to the front face of R8 is very small or negligible. However, the horizontal stress from the