Full Length Article

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

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A B S T R A C T

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 afield inspection indicated that 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.

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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), Stazhevsksii (1996), Hustrulid (2000), Rustan (2000), Quinteiro et al. (2001a), Power (2004), Sellén 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 Naarittjavi (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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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 drift 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 $S_0$) just reaches the position $S_0$ 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
intact rock mass (above the upper surface in Fig. 3c) in Y-direction is not zero. In addition, it is assumed that the horizontal stress in Y-direction from the waste rock below the boundary JK in Fig. 3c is not zero since the flow ability of the waste rock along JK is smaller than that along JI where waste rock (also ore fragments) can flow down during extraction. In brief, the rock in an ordinary ring bears two directional loads, one in vertical direction (Z-axis in Figs. 2 and 3) and the other in horizontal direction (Y-axis).

In the first type of hanging roofs, such as one of roofs of R1–R12 in Fig. 2, the partly free surface in front of the ring to be blasted does not exist at all. The ore mass in the left and above the position $S_E$ (shown in Fig. 2) is mostly an insufficiently fragmented mass. In this
case, for the ring to be blasted, there are three directional stresses acting on the rock mass in the ring. Two horizontal stresses in X- and Y-directions can be considered to be equal to the in-situ stresses in this mining area. In the second type of hanging roofs, the partly free surface in front of the ring (e.g. R10 in Fig. 3) to be blasted disappears. There is one partly free surface (e.g. at R8 in Fig. 3), but it is far from the ring in question (e.g. R10).

As a conclusion, the rock mass in a hanging roof bears three directional loads, while that in an ordinary ring does two directional ones.

2.2.2. Free surface

In an ordinary ring, there is a partly free surface in the front of ring, as described above. This surface is approximately parallel to the plane of the ring. Such a plane is indicated by the dashed lines with ring numbers in Fig. 2. It is this partly free surface that makes the blast-induced compressive waves partly reflected into tensile waves. In other words, this partly free surface plays an important role in rock fracture and fragmentation. However, in the first type of hanging roofs, such a partly free surface does not exist anymore. In the second type of hanging roofs, this partly free surface is at least two burdens far from the ring to be blasted. In this case, when a compressive wave arrives at the partly free surface, its amplitude will be much smaller than that in an ordinary ring due to wave attenuation. As a consequence, the tensile wave reflected from the partly free surface will be small, giving rise to little spalling or even no spalling in the ring if it is blasted as usual. In other words, the usual blast method fails to break down a hanging roof. In order to destroy a hanging roof, higher amplitude of stress wave must be supplied.

2.2.3. Confining pressure

As mentioned above, in an ordinary ring, the rock bears only two directional loading, i.e. the stress in one horizontal direction, defined as h1 direction, is nearly zero, i.e. $\sigma_{h1o} = 0$, here subscript letter “o” means ordinary rings. In a hanging roof, the rock bears three directional loading, and the stress in the same horizontal direction $h_1$ is greater than zero, i.e. $\sigma_{h1} > 0$, here “r” means hanging roof. It is assumed that the stresses in another horizontal direction, defined as h2 direction, are equal to each other in both an ordinary ring and a hanging roof, i.e. $\sigma_{h2o} = \sigma_{h2r}$.

The magnitudes and orientations of two horizontal stresses in Malmberget mining area can be estimated by using the following formulae (Sandström and Nordlund, 2004):

$$\sigma_{h1} = 0.037z$$  \hspace{1cm} (1)

$$\sigma_{h2} = 0.028z$$  \hspace{1cm} (2)

where $z$ is the vertical distance or depth from the surface, i.e. $z = 0$ m on the surface.

Eq. (1) is for the maximum horizontal principal stress in MPa (East-West), and Eq. (2) is for the minimum horizontal principal stress in MPa (North-South). Note that the calculated stresses by using Eqs. (1) and (2) fall in the range of the empirical formula by Brown and Hoek (1978).

Since mining activity and underground structures affect the local stress state, it is difficult to determine the exact stress magnitude and orientation in a hanging roof. To break down a hanging roof, it is better to take the maximum horizontal stress into consideration and assume that both horizontal stresses in two directions are equal. Accordingly, Eq. (1) is used to estimate the maximum horizontal stress. In this study, for the three hanging roofs to be discussed later, their depths are $z_1 = 440$ m, $z_2 = 437$ m, and $z_3 = 480$ m, respectively. Accordingly, their maximum horizontal stresses, i.e. the confining pressures, are as follows:

(1) For the first hanging roof at JS4402-r52:

$$\sigma_{h1} = 0.037z_1 = 16.3 \text{ MPa}$$  \hspace{1cm} (3a)

(2) For the second hanging roof at JH4376-r7:

$$\sigma_{h2} = 0.037z_2 = 16.2 \text{ MPa}$$  \hspace{1cm} (3b)

(3) For the third hanging roof at JS4801-r20:

$$\sigma_{h3} = 0.037z_3 = 17.8 \text{ MPa}$$  \hspace{1cm} (3c)

2.3. Rock fracture under confining pressure

The above description indicates that, in order to break down a hanging roof, two factors must be considered: increased confining pressure and reduced free surface. To consider the effect of increased confining pressure on rock fracture, we need to know the influence of confining pressure on the strengths and fracture toughness of rock.

Experimental studies including Lindholm et al. (1974), Gowd and Rummel (1977), Schmidt and Huddle (1977), Whittaker et al. (1992), Thallak et al. (1993), Vasarheleyi (1997), Al-Shayeaa et al. (2000), Backers et al. (2002), Funatsu et al. (2004), and Liu et al. (2014) have shown that rock compressive strength and fracture toughness increase with increasing confining pressure. Unfortunately, the studies on fracture toughness only deal with static or quasi-static loading. Similarly, the experiments on dynamic tensile strength with different confining pressures are few. Since compressive strength and tensile strength of rock have an approximately linear relation, it is assumed that the dynamic tensile strength of rock increases with increasing confining pressure, too. Because there are no measured data on the iron ore available, we need estimate the dynamic strength of the ore under different confining pressures. Two results for basalt (with a statically uniaxial compressive strength of 369 MPa) (Lindholm et al., 1974) and amphibolite (with a statically uniaxial compressive strength of 140 MPa) (Liu et al., 2014) may be taken as references. According to the results in Lindholm et al. (1974) and Liu et al. (2014), as confining pressure is increased to 20 MPa, the dynamic strength of the basalt is increased by 5% and that of the amphibolite increased by 45% approximately. It is assumed that the ore mass in the hanging roofs to be discussed is more close to the amphibolite. Thus, in order to destroy the hanging roofs, we have to apply a 45% higher stress to overcome the higher strength caused by the higher confining pressure.

3. Shock wave collision and stress superposition

As described above, a higher stress (as well as more energy) is required to break down a hanging roof due to the increased confinement and reduced free surface. This may be realized by drilling more and larger boreholes to charge more explosive. Unfortunately, it is not allowed to perform any drilling operation in or close to a hanging roof in the mine. Because of this limitation, it is necessary to look for another way. A possible and easy way is to make use of shock wave collision and stress superposition.

3.1. Shock wave collision

According to one-dimensional (1D) shock wave theory (Cooper, 1996; Zhang, 2016), when one shock wave with pressure $P_1$ meets...
another shock wave with pressure $P_2$, the final shock pressure $P_3$ produced is greater than the sum of the initial two shock pressures, i.e.

$$P_3 > P_1 + P_2$$

(4)

This is called shock wave collision. Note that a shock wave collision is different from an elastic wave collision. For example, as two shock waves each with a 15 GPa pressure travel towards each other in TNT (cast), their collision can result in a 47.5 GPa pressure, much higher than the sum of the initial two pressures (Zhang, 2016). In 1D condition, as an elastic wave with stress $\sigma_1$ meets another one with stress $\sigma_2$, the final stress $\sigma_3$ produced is equal to the sum of the stresses of the initial two elastic waves, i.e.

$$\sigma_3 = \sigma_1 + \sigma_2$$

(5)

Take a single blasthole for example, as shown in Fig. 4. In this hole, there are two primers at locations D1 and D2. There is no free surface surrounding the hole that is fully charged. It is assumed that: (1) a shock wave from a detonating blasthole quickly decays to an elastic wave in the rock mass, so shock wave collision will be only considered in the blasthole, while elastic wave superposition will occur in the rock mass; (2) the detonation velocity of the explosive and the P-wave velocity of the rock mass are equal to each other; (3) in order to simplify the analysis, only P-wave is considered while S-wave is neglected. Under these conditions, when the two primers are simultaneously initiated, the detonation from both primers will travel in two directions: up and down in the hole. When the detonation front from D1 propagates down to D2, its front in upward direction will come to F1. At the same time, when the detonation front from D2 propagates up to D1, its front in downward direction will come to F2. At the same moment, the fronts of the P-waves starting from D1 and D2 will travel outward in the rock mass. These fronts are indicated in Fig. 4. Now a summary on the stress distribution in the rock mass can be made as follows:

1. There is a superposition region of the two P-waves starting from the two primers, which is enclosed by curve E1-D1-E2-D2-E1. In this region, the stress (in a certain direction and at a specific point) is greater than either the initial stress (at the same direction and same point) caused by the wave starting from D1 or the initial stress from D2.
2. In the superposition region E1-D1-E2-D2-E1, there are three areas. The first is the circular area, and the diameter of which is D1-D2 or B1-B2. In this area, a shock wave collision happens between D1 and D2 in the hole, and the collision begins at location O. According to Eq. (4), this shock collision results in that the final shock pressure is greater than the sum of the initial two shock pressures. Accordingly, the final stress produced by the shock collision in this circular area must be greater than the sum of the initial two stresses each from one primer. With elapsed time, this circular area expands outward.
3. In the superposition region E1-D1-E2-D2-E1, the two other areas are E1-D1-B1-D2-E1 and D1-E2-D2-B2-D1. In these areas, only elastic wave superposition may occur, i.e. the final stress after superposition is greater than either of the initial two stresses but less than or equal to the sum of the two initial stresses.

As a result, if two primers are placed at two places in a blasthole and they are initiated simultaneously, the stresses at a certain point in some region will be two times greater than the stresses at the same position caused by a single primer. Since a normal production blasthole contains only one primer in the mine, it is possible to break down the hanging roof by placing multiple primers in one or more holes in a ring. However, there are more factors to be considered, such as loading rate effect on rock fracture.

3.2. Elastic wave superposition

If we place four primers at different positions D1–D4 in two blastholes and all of them are initiated simultaneously, as shown in Fig. 5, after a certain period of time, four fronts of P-waves starting from every primer location come to the positions indicated by four circles in Fig. 5a. There is an intensive stress superposition region surrounded by D1-D3-D4-D2. Within this region, there are four smaller regions where stresses coming from 3 P-waves start at three primers. These regions are marked with number 3. If only elastic wave superposition is considered, the final stress at an arbitrary point in these regions will be less than or equal to three times of the stress at the same place from any one primer detonation. In addition to these small regions, there is another area enclosed by area QRST in the central part of Fig. 5a. In this area, the final stress at an arbitrary point results from the superposition of four initial stresses from four primers. Similarly, if only elastic wave superposition is considered, the final stress at a certain point in this area may reach four times of the stress at the same point due to one primer detonation. Obviously, if the shock collision is considered, the final stresses in some parts of this area will be greater than four times of the stresses at the same positions. If we take two sections $A$–$A$ and $B$–$B$ from Fig. 5a, then we find that the area QRST is actually a three-dimensional zone. On section $A$–$A$ this zone is the area enclosed by $URVT$ and on section $B$–$B$ it is the area surrounded by $QUVS$. Enclosed in this zone are two smaller zones induced by shock collision. The two smaller zones are indicated by the dashed circles. In these two zones, the total stress at a certain point may be greater than four times of the stress caused by one single primer detonation.

3.3. Loading rate effect on rock fracture

Experimental investigations including Olsson (1991), Zhang et al. (1999, 2001), Cho et al. (2003), Dai et al. (2010), and Xia and Yao (2015) have shown that rock strengths and fracture
toughness increase with increasing loading rates under dynamic loading condition. When shock collision in the same hole and elastic wave collision between holes happen, the loading rate in the rock mass surrounding the blastholes will increase. According to previous experimental studies summarized in Zhang (2016), under dynamic loading condition, the relation between strain rate $\dot{\varepsilon}$ and tensile strength $s_{Td}$ of rock and that between loading rate $\dot{k}$ and mode I fracture toughness $K_{Id}$ of rock can be expressed as

$$s_{Td} = C_{01} \dot{\varepsilon}^a$$

$$K_{Id} = C_{02} \dot{k}^b$$

where $C_{01}$ and $C_{02}$ are the coefficients; and constants $a$ and $b$ are equal to 0.33 and 0.67–0.76, respectively. Let $\dot{\varepsilon}_1$ and $\dot{k}_1$ be the strain rate and loading rate under the condition of a single primer in a blasthole, and corresponding strength and toughness be $s_{Td1}$ and $K_{Id1}$, respectively. As four primers are placed in two holes as shown in Fig. 5, we assume that the maximum strain rate and loading rate in the high stress superposition zone are approximately four times as great as $\dot{\varepsilon}_1$ and $\dot{k}_1$, respectively. Then we may estimate from Eqs. (6) and (7) that the tensile strength and the fracture toughness will be 1.58 and 2.51–2.86 times as great as $s_{Td1}$ and $K_{Id1}$, respectively. This means that, to break down the hanging roof, a higher stress is required to overcome the higher strength and greater toughness.

As a consequence, if the rock strength or fracture toughness is increased by up to 3.31 times due to increased confining pressure and increased loading rate, it is possible to break down the hanging roof by placing four primers at different positions in two neighboring blastholes.

4. New method and its applications

4.1. New method for breaking down hanging roofs

On the basis of the above analysis, the stresses at any point in some region between two neighboring blastholes containing four primers with the same delay time can be greater than four times of the stresses at the same point caused by a single primer in a blasthole. That is to say, a much high stress can be achieved by making use of shock collision and elastic wave superposition, without increase in explosive charge. Although four primers at two holes are good enough to overcome the higher rock strengths and greater fracture toughness caused by the greater confinement and higher loading rate in a hanging roof, it is better to use more than four primers at the two holes so as to certainly break down the hanging roof. Accordingly, the ring nearest the hanging roof, for example R13 in Figs. 2 and 3, is chosen to do this special blasting. In such a ring, multiple primers are placed at different positions in two neighboring blastholes, and all these primers are initiated at the same time. This special blast method is called new method for...
breaking down hanging roofs. The new method consists of two key issues:

1. To place several primers at different positions in two neighboring holes. All primers in the two holes are initiated at the same time. If NONEL or pyro-technic detonators are used, the zero delay time should be chosen.

2. The delay time between the above two holes and the next hole to be fired must be very long so that the fragments from the two hole blasting have enough time to completely fall down before the next hole is initiated.

4.2. Breaking down the first hanging roof

The first hanging roof was formed before ring JS4402-r52 (r52 in short) in a sublevel drift named JS4402 located in a small and narrow ore body. This is a second type of hanging roof. Ore extractions in two nearest rings r51 and r50 were less than 50% because their roofs were remained. The new method was applied to ring r52 and the photograph in Fig. 1b was taken before ring r52 had been charged. The blast plan of r52 is shown in Fig. 6. Two holes #6 and #7 were blasted simultaneously. A total of 7 primers were placed at different locations in the two holes and they were initiated at the same time. Every primer contained one NONEL detonator. Considering that the initiation error of NONEL detonators increases with increasing delay time, zero-delay-time detonators were used in the 7 primers. Thus, according to the above analysis, the blast-induced stresses in some area between the two holes could reach 7 times greater than the stresses in a normal production blast in which only one primer is placed in each hole.

As stated above, in order to have enough time to let fragments from the first two holes fall down, a delay time of 500 ms was assigned to the next initiation – hole #8. If blasting in holes #6–#8 is successful, a free surface and an empty room will be created. If so, the rest of holes in the ring may be blasted one by one as in normal production blasting. For this reason, a delay time of 100 ms or 200 ms was used between these holes, as shown in Fig. 6. Note that three primers were placed in each of holes #8–#9 and #1–#5. This is to assure that the roof is certainly broken down.

After the blast of r52, the hanging roof came down and ore extraction in r52 reached 110%, a normal value in the mine.

4.3. Breaking down the second hanging roof

The second hanging roof belongs to the first type and it was formed from the open cut in the drift JS4402. Ore extraction in the first 6 rings were lower than 80% on average and the extraction in the last ring r6 (in short) was only 23%. This hanging roof was broken down by blasting ring r7. Different from the first hanging roof, the second one was formed from the beginning of the drift, similar to the situation shown in Fig. 2. In this case, the front free surface was reduced to nearly zero for ring r7. Considering this increased confinement, two long holes were chosen as the first simultaneous initiation, and a total of 8 primers were placed in the two holes, as shown in Fig. 7. In addition, since the increased confinement could result in longer time for rock fragments to fall down, a long delay time of 3 s was given to the next initiation – hole #4. As a result, the hanging roof was broken down and the ore extraction came back to a normal level in ring r7 and other following rings.

4.4. Breaking down the third hanging roof

The third hanging roof is of the first type of hanging roof formed from the open cut in the drift JS4402. Ore extraction in the first 19 rings (r1–r19 in short) was only 45% on average. The third roof was broken down by blasting ring JS4801. This roof is very similar to the second one. The last ring before ring 20 is the ring 19 in which the final extraction was only 5%, i.e. most of the ore mass in ring 19 was remained. Two pictures in Fig. 8 were taken while ring 20 was being charged. Fig. 8b indicates that the ore mass close to the brow (top contour of the drift) is hanging there, although the ore mass looks fractured. However, it is difficult to judge how the ore mass inside ring 19 had been fractured. In brief, ring 20 was highly confined.
In terms of the above description, a similar blast plan as in the second hanging roof was employed. As a consequence, the third hanging roof was broken down, too. In addition, the ore extraction in ring 20 reached 119%. When the loading in ring 20 was finished, a photograph was taken, as shown in Fig. 9, from which we can see a certain burden for ring 21 was intact and the brow damage is much less than that for ring 20.

5. Effect of new method on stability of nearby structures and vibrations in far field

5.1. Stability of nearby structures

After each hanging roof was broken down, an investigation was made on the stability of structures in the mine. In the far field of each drift where a hanging roof was located, no damage in the roof and walls of the drift was found. No damage was observed in other neighboring drifts, either.

In the drifts close to the hanging roofs, no damage was found in the tops of drifts JS4402 and JH4376. Fig. 10 indicates that the shotcrete in both top and walls of drift JS4402 is complete, i.e. no damage. Differently but not strangely, small spalling was found in the left side of drift JS4801 where the third hanging roof was located. We can see from Fig. 8a that before the roof was broken down, there was already spalling in the left top of drift, but no damage in the right side. After the hanging roof was broken down, as shown in Fig. 9, there was still no damage in the right side, while the new spalling in the left side was observed. Probably, the previous spalling shown in Fig. 8a is one of main factors that cause the new spalling.

Another positive result is that the brow damage was reduced by breaking down the third hanging roof. As indicated in Fig. 8a, the burden for ring 20 was completely broken off before the hanging roof was destroyed. Note that the boreholes observed in Fig. 8b are all under the hanging roof, and the picture was taken under the roof. However, a burden with several collars can be clearly seen in Fig. 9 after the hanging roof was broken down, implying that the brow damage was decreased when the roof was destroyed.

5.2. Vibrations in far field

In Malmberget City, a vibration monitor is all time installed at the basement of one house. Any vibrations above the trigger level of the monitor can be recorded. Among the three hanging roofs, the second one at JH4376-r7 was nearest to the monitor, while the other two at JS4402-r52 and JS4801-r20 were relatively far from the monitor. As a consequence, the ground vibrations from production blasts in the drift JH4376 were always recorded by the monitor.

Fig. 11 shows the maximum vertical particle velocity per week recorded by the monitor in the city from 2000 to 2010 (Zhang, 2012). When the second hanging roof was broken down in JH4376 on April 1, 2004, the maximum vertical particle velocity found to be 5.85 mm/s. This value is much lower than two nearest high vibrations, one is 15.8 mm/s caused by a failed open cut in the drift JH4376 happening on March 28, 2004, and the other is 16.2 mm/s occurring on May 17, 2004 due to a simultaneous blast of two rings in two different drifts. It should be noted that, in the failed open cut blast, several blastholes were connected one another, resulting in the explosive charged in the connected holes being initiated together. Similarly, in the simultaneous initiation of two rings, the measured vibrations came from the superposition of two vibration waves from the two rings.

Since the monitor was relatively far from the other two hanging roofs at JS4402-r52 and JS4801-r20, there were no measured vibrations available.

6. Discussion

6.1. Safety of new method

As mentioned above, no damage was found in the far field rock structures when the three hanging roofs were broken down. In addition, no damage was observed in the near field drifts when the first and second roofs were destroyed. Only in the near field of drift
JS4801 was spalling observed in the left side of the drift, probably due to the previous damage. Moreover, the maximum vibration during breaking down the hanging roof at JH4376-r7 was found to be much smaller than that during simultaneous blasting of two rings. These results indicate that the new method is safe for both nearby structures and far field vibrations. Two possible reasons are:

1. Much energy included in the high stresses caused by shock collision and elastic wave superposition might be consumed in fracturing the rock close to and between the two first-initiated holes, e.g. in the regions enclosed by the dashed circles and shadowed areas in Figs. 5 and 6. As a consequence, the waves propagating to the rock outside the two holes and the far field will significantly decrease.

2. As soon as going into rock mass, a shock wave will rapidly decay to an ordinary stress wave or elastic wave. A support to the first reason is that when shock collision was applied to production blasts in which two primers were placed at different positions in each hole and they were initiated at the same time, the brow damage was largely reduced rather than increased (Zhang, 2011, 2014a).

6.2. Quantity of primers and delay time

It is necessary to do a further study on the quantity of the primers in the first two holes. The similar thing is for the delay time between the first initiation and the next one. In practice, if it is difficult to determine the confining pressure and the falling speed of fragments, seven or eight primers in the first two holes and a delay time longer than 1 s between the first two holes and the next hole are suggested.

6.3. Reasons for hanging roofs and hang-ups

It is of importance to investigate every reason for hanging roofs in detail in the future. However, some possible reasons can be listed as follows: (1) too short opening slot in a sublevel drift, as described in Section 2; (2) too small charged lengths in some holes in a ring, which result in that the stresses and energy transmitted to the upper part of the ring are not strong enough to make sufficient fragmentation in the upper part; (3) an improper blast plan such as incorrect primer placement; (4) detonation failure in some holes in a ring; (5) an increasing confinement to the ore flow (Hustrulid and Kvatil, 2008; Castro et al., 2014); and (6) other unknown reasons.

6.4. Breaking down a hanging roof or a high hang-up at good time

Even though a spalling in a drift surface can happen far from explosive charge, e.g. 10–20 m, a short distance between the charge and the drift surface resulted in larger volume of rock fracture in the surface, according to field investigation and spalling theory (Zhang, 2014c, 2016). Therefore, as soon as a hanging roof occurs, it should be broken down as early as possible so that the distance between the nearest free (or partly free) surface and the ring to be blasted is kept as small as possible. If a hang-up does not break up by itself, it may be broken down by using the new method.

7. Conclusions

A hanging roof makes the ore mass in a ring to be blasted bear three directional loadings. In other words, the confining pressure to the rock mass in the hanging roof is increased from zero to a certain value. This increase in confining pressure requires a higher stress or more energy to break down the hanging roof. In addition, the reduced free surface makes tensile rock fracture decreased. Based on these facts, a new method for breaking down a hanging roof has been developed. This new method has been used to break down all three hanging roofs met in one mining area in the Malmberget mine.

The new method is easy to be used, very cheap and efficient. By using this new method, a large ore loss due to the old method can be avoided.
The new method is safe for either nearby structures or the far field, regarding rock damage and ground vibrations.

Conflict of interest

The author wishes to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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References

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