Effect of double-primer placement on rock fracture and ore recovery

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Zongxian Zhang
University Centre in Svalbard (UNIS)
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Effect of double-primer placement on rock fracture and ore recovery

Z.X. Zhang

Department of Arctic Technology, The University Centre in Svalbard, Longyearbyen, Norway

1. Introduction

The placement of a primer (usually containing a detonator) in a blasthole plays an important role in rock blasting. Unfortunately, the importance of primer placement in rock fracture, fragmentation, and even ore recovery has not been well understood so far. An improper or even wrong primer position in engineering can still be found.

As only one primer is placed at each blasthole, the study in [1] by means of stress wave analysis shows that the best primer position is the middle of charged blasthole, in terms of detonation energy efficiency, rock fragmentation, and rock break in the roof of a drift. The production blasts had well confirmed the above theoretical analysis since the ore extraction and recovery had been largely increased, and the eyebrow break markedly reduced by the middle-primer method, compared with the old method used in the mine [1].

It is common practice for some operators to routinely put two primers into a blasthole, and their rationale is that using a second primer is insurance against either a poor initiator/detonator or a cutoff of the hole due to shifting rock caused by a previous delay firing [2]. In many mines and quarries, two primers are often placed in each blasthole. However, in many cases, one primer is placed at the bottom and the other close to the collar of a blasthole. The latter is usually taken as a backup in case of that a malfunction occurs for the bottom primer. In this primer placement, if the two primers are initiated at the same time, the collar primer will produce serious back break and even bring about a lot of detonation energy loss. If the collar primer is initiated later than the bottom one, the result is not good, either. In brief, a two primer placement with one primer close to collar should be avoided. The above description indicates that if two primers are placed in one blasthole, their positions are to be chosen scientifically. In this paper, the double-primer placement means that two primers with same delay time are placed at correct positions in a blasthole.

When this double-primer placement is applied to a blasthole, a collision of shock waves from two primer locations will happen. Different from elastic wave collision, a shock wave collision results in that the final pressure produced is greater than the sum of the initial two pressures. Stress analysis indicates that this should be favorable to rock fracture and fragmentation in blasting. This double-primer placement was tested in Malmberget mine by using electronic detonators, aiming to improve rock fragmentation. At the same time, another method, named DRB (Dividing Ring Blasting), was tested, too. Two production drifts in an ore body were taken as test drifts. In each test drift both methods were tried. For comparison, two nearest production drifts to the test drifts were taken as reference drifts. The results showed that on average the double-primer placement recovered more iron ore than either the DRB method or the ordinary method used in the reference drifts. In addition, fragmentation looked much finer and the eyebrow break became much less for the double-primer rings, compared with the reference rings.

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When this double-primer placement is applied to a blasthole, a collision of shock waves from two primer locations will happen. Different from elastic wave collision, a shock wave collision results in that the final pressure produced is greater than the sum of the initial two shock waves, according to shock wave theory [3]. An experimental study by Dawes et al. [4] well confirmed this theory in rock blasting. Their experiments showed that the amplitude of stress waves in rock mass due to two-primer placement in a blasthole was much greater than the double of the amplitude of the waves caused by one single primer in a similar blasthole. Their experiments indicate potential applications of a two-primer placement in rock blasting. After a long time when electronic detonators came into being, shock collision theory was used to improve fragmentation at Salvador mine [5]. Even by using NONEL detonators, the shock collision theory was applied to break down remained roofs in sublevel caving mining [6]. Due to the success in breaking down remained roofs, this theory was applied to reduce eyebrow break in Malmberget mine by NONEL detonators [7]. In order to further improve rock fragmentation in the same mine,
from 2011 to 2012 two blast methods were tested by using electronic detonators, one is DRB (Dividing Ring Blasting) method, originally developed for vibration control [8,9], and the other is the double-primer placement. In the DRB method, one ring is separated into two parts – upper one and lower one – in charging and blasting. The blastholes in the lower part of a ring whose upper part has been blasted in previous blasting are blasted one by one with a delay time between two neighboring holes, and then in the same blast the blastholes in the upper part of the next ring are initiated one by one with a delay time. In this way, the explosive in each delay time can be reduced by about 50% if the blastholes in a ring are divided at their middles. In order to improve the fragmentation in the upper part of a sublevel ring, a 10 ms delay time between two neighboring holes was employed in the upper parts of the DRB rings.

In terms of the above description, we will briefly introduce the shock collision theory, show how the stress and energy distributions are changed due to shock wave collision, and analyze the effects of shock collision on rock fracture and fragmentation. Then the test results for the double-primer placement in the mine will be presented and discussed.

2. Theory on shock wave collision

According to one-dimensional shock wave theory [3], when one shock wave with pressure \( P_1 \) meets another shock with pressure \( P_2 \), the final shock pressure \( P_3 \) produced is greater than the sum of the pressures of the initial two shock waves, i.e.

\[
P_3 > P_1 + P_2 \tag{1}
\]

This case is called shock wave collision. A shock wave collision is different from an elastic wave collision. In one-dimensional condition, as an elastic stress wave with stress \( \sigma_1 \) meets with another elastic wave 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. \( \sigma_3 = \sigma_1 + \sigma_2 \).

In shock wave collision, the final pressure depends on both initial two shock pressures and the material. In the following, we will see how much the final pressure is increased by shock collision, taking TNT (cast) as an example. Assume a shock A with pressure \( P_1 = 15 \text{ GPa} \) travelling in positive direction in the explosive (one-dimensional), as shown in Fig. 1. In the same explosive there is another shock B with pressure \( P_2 = 15 \text{ GPa} \) travelling in negative direction. The Hugoniot values for TNT (cast) are \( \rho_0 = 1.614 \text{ g/cm}^3 \), \( C_0 = 2.39 \text{ km/s} \), and \( s = 2.05 \) [3]. When the two shock waves approach each other head-on, the collision will cause two new shock waves that are reflected back in each direction.

We start with the Hugoniot curve for the new wave in negative-\( x \) direction. This Hugoniot is coming from state \( P_1, u_1 \), and that \( u_1 \) is positive, see Fig. 1 and Fig. 2. This state was arrived at by the initial shock B in negative-\( x \) direction, into \( u_0 = 0 \) material. The Hugoniot curve of this initial shock is

\[
P = \rho_0 C_0 u + \rho_0 s u^2 \tag{2}
\]

Since \( P_1 = 15 \text{ GPa} \), we get \( u_1 = 1.625 \text{ km/s} \) from Eq. (2). The Hugoniot curve for the new shock in negative direction must be rotated around this point and will intercept the \( P_0 = 0 \) or \( u \) axis at \( 2u_1 \) (see Fig. 2), and its equation is

\[
P = \rho_0 C_0 (2u_1 - u) + \rho_0 s (2u_1 - u)^2 \tag{3}
\]

Now we consider the Hugoniot curve for the new wave in positive-\( x \) direction. This Hugoniot is coming from state \( P_2, u_2 \), and that \( u_2 \) is negative; see Figs. 1 and 2. This state was arrived at by the initial shock B in negative-\( x \) direction, into \( u_0 = 0 \) material. The Hugoniot curve of this initial shock is

\[
P = \rho_0 C_0 (u_0 - u) + \rho_0 s (u_0 - u)^2 \tag{4}
\]

Since \( P_2 = 15 \text{ GPa} \), \( u_0 = 0 \), we get \( u_2 = -1.625 \text{ km/s} \) from Eq. (4). The Hugoniot curve for the new shock in positive direction must be rotated around this point and will intercept the \( P_0 = 0 \) or \( u \) axis at \( 2u_2 \) (see Fig. 2), and its equation is

\[
P = \rho_0 C_0 (2u_2 - u) + \rho_0 s (2u_2 - u)^2 \tag{5}
\]

The solution for the particle velocity after the collision can be obtained from equating the two Hugoniot Eqs. (3) and (5). This gives rise to

\[
u_3 = 0 \tag{6}
\]

Then the pressure at the interaction can be obtained by using this particle velocity in either Eqs. (3) or (5):

\[
P_3 = 47.5 \text{ GPa} \tag{7}
\]

Obviously, \( P_3 = 47.5 \text{ GPa} \) is much greater than the sum \( P_1 + P_2 = 30 \text{ GPa} \) of the initial two pressures. In brief, the final pressure caused by shock wave collision is greater than the sum of the initial two shock waves.
3. Double-primer placement on stress and energy distributions

3.1. Stress distribution

In rock blasting, all energy used in rock fracture and fragmentation comes from the detonation wave that consists of a leading shock wave and a rarefaction wave (or Taylor wave). In addition, rock fracture and fragmentation depend not only on the amount of energy applied to rock, but also on stress amplitude, stress distribution, loading rate, etc. Because a shock wave collision can produce a greater pressure (stress) than the sum of initial two pressures, the final stresses in a certain region produced by the shock collision will be greater than the double of the stresses in the same region caused by a single primer placement. These greater stresses are useful for rock fracture.

Now we take one blasthole in a sublevel caving ring as an example to see the stress distribution due to shock wave collision, as shown in Fig. 3 in which other blastholes in the ring are not shown. In this blasthole, there are two primers at locations D1 and D2. The charge length is F1–F2 and primer positions D1 and D2 are at 1/3 and 2/3 of F1–F2, respectively. There is no free surface in either left or right side of the lower part of a sublevel caving ring. In the upper part of the ring, there are two partly-confined surfaces. The blasthole is fully charged. We assume that: (1) the P-waves shown in Fig. 3 are all compressive (since detonation is just approaching the ends of explosive charge); (2) effect of S-waves on stress distribution is neglected since S-waves start later than P-waves; (3) 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 stress wave superposition will be handled in the rock mass; (4) the detonation velocity of the explosive and the P-wave velocity of the rock mass are equal to each other. 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. Now we can make a summary on the stress distribution at the moment shown in Fig. 3, as follows:

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 final stress is greater than either of the initial two stresses starting from D1 and D2.

In the superposition region E1–D1–E2–D2–E1, there are three areas. The first is the circular area the diameter of which is D1–D2 or B1–B2. In this area, a shock wave collision happens, and the collision begins at location O as soon as the initial two shocks arrive at this location. According to formula (1), this shock wave collision results in that the final shock pressure is greater than the sum of the initial two shock pressures. Accordingly, the final stresses produced by the shock collision in this circular area must be greater than the sum of the initial two stresses. With increasing time, this circular area expands outward. This shock collision effect on the increase in stresses is well confirmed by the field measurement [4], indicating that the maximum stress caused by two primers at different positions in a blasthole, which are instantaneously initiated, is markedly greater than the double of the maximum stress induced by one single primer in a similar borehole.

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 two areas, elastic stress wave superposition occurs, i.e. the final stress after superposition is greater than either of the initial two stresses.

As a result, if two primers are placed at two different places in a blasthole and they are initiated simultaneously, in the rock surrounding the blasthole, the stresses will be efficiently superimposed. In some regions the final stresses by the double-primers will be greater than the double of the stresses by a single primer; in other regions the final stresses will be greater than the stresses by a single primer. We have noted that Fig. 3 is in the plane of the ring, so each circle in the figure actually represents a spherical region in the rock. The stress waves starting from D1 and D2 are in fact two complex spherical waves, so is the wave (indicated by the circle between D1 and D2) from the shock collision. The superposition of these compressive P-waves is favourable to rock fracture and fragmentation, since in a spherical compressive wave the stresses in two tangential directions are often tensile.

A number of experimental studies such as in [10,11] have demonstrated the radial cracks induced by compressive P-wave in blasting.

In addition to the stresses on the plane of the ring, it is necessary to know the stress distribution in the cross section along the axis of drift, as shown in Fig. 4. At the same moment as in Fig. 3, two compressive P-waves from D1 and D2 are indicated by two large trimmed circles. At the same time, a small circle between D1 and D2 is also a compressive wave region due to the shock wave collision. These three compressive waves will be efficiently superimposed one and another in the region between D1 and D2, and this superposition will be strengthened with time. As mentioned above, the superposition of compressive waves is useful for rock fracture.

As well as we know, a compressive wave will be reflected into a tensile wave at a free surface (also at a partly free surface). Such a tensile wave is dependent on the original compressive wave, i.e. the greater the compressive wave, the greater is the tensile wave. Therefore, a higher final compressive wave will be reflected into a higher tensile wave. In Fig. 4, we can see the reflected wave occupied by S1–M1–S3–S1 and S2–M1–S4–S2. They are well

![Fig. 3. Stress distribution in the plane of a sublevel caving ring. Explosive is charged in the blasthole between F1 and F2, and the primers are placed at D1 and D2.](image)
distributed in the ring. With increasing time, the collision-caused compressive region becomes larger and larger, and relevant tensile stresses reflected from the front face will be greater and greater. As a consequence, the rock in the ring will be highly fractured and fragmented.

3.2. Energy distribution

The shock collision makes the total detonation time in the blasthole shorter, resulting in a greater energy concentration. As shown in Fig. 4, the total detonation time $T_D$ in the hole is equal to $T_D = l_{dh}/3D$ in the double-primer case shown in Fig. 4, $T_D = l_{dh}/D$ in the case of one primer at either the bottom or the collar of the hole, and $T_D = l_{dh}/2D$ in the case of one primer at the middle of the hole. Among these three cases, the double-primer case gives the shortest detonation time, meaning that the total detonation energy is distributed in a shortest period of time, compared with two other cases. This high energy concentration in the double-primer case should be helpful for rock fragmentation.

At last, we note that at the same moment as in Fig. 4, when all explosive in the hole is detonated, no tensile wave reaches the eyebrow and roof of the drift. In other words, the eyebrow break and rock fracture in the roof can be reduced by the double-primer placement.

4. Production tests on double-primer placement

4.1. Location of tests

In order to improve fragmentation, it was planned to test the DRB method first and the double-primer one second. Considering as small effect of geological factors on blasting as possible, four neighboring production drifts in a production level were taken as the test area. Two middle drifts 496 and 499 are planned to use the two test methods, and two others 493 and 502 as reference drifts. The locations of these drifts are shown in Fig. 5. In each drift, blasting begins from hanging wall. Therefore, ring 1 (R1) is always blasted first, and the others follow one and another in sequence.

4.2. Blast plan

In theory, as shown in Figs. 3 and 4, in order to achieve good fragmentation, two primers are to be placed at 1/3 and 2/3 charged parts of each blasthole. However, considering a sublevel ring is a fan form of borehole distribution, the specific charge in upper part of the ring is much smaller than that in the lower part. Thus, in real blast plans, we often place the two primers at higher positions than that shown in Figs. 3 and 4. A real charge plan is shown in Fig. 6 where the primer positions are shown by small squares. Also, the upper primer in the middle blasthole is at 30 m high from the drift roof due to limited length of detonator wires. Anyway, the position of a primer in the double-primer placement can be changed more or less, according to practical situations.

5. Results from double-primer placement in sublevel caving

5.1. Rock fracture in eyebrow region

As mentioned previously, the double-primer placement was successfully used to reduce eyebrow break in sublevel caving by using NONEL detonators in the same mine Malmberget [7]. The result indicated that the eyebrow break was reduced from 3 m in ordinary rings (in which the same primer placement was used as in the reference rings in this study) to 2.1 m in the double-primer rings. Note that the burden is 3.5 m in both ordinary and double-primer rings. As electronic detonators were used in this study, result became even better, due to the accurate initiation of electronic detonators which makes shock collision effect better. Fig. 7a shows the result for eyebrow break from one double-primer ring in which a large part of burden is remained after blasting. This result was found in most of the double-primer rings we had tested. In this case, all of collars are visible. Therefore,
chargers do not need to go to the caving area to find the collars during charging. In other words, the work safety for miners is much better. As a comparison, Fig. 7b indicates the result for eyebrow break from a reference ring in which a small part of burden is remained.

5.2. Rock fragmentation

According to the author’s field observations, the fragmentation from most double-primer rings looked fine, as the muckpile shown by the picture in Fig. 8a that was taken after blast and when loading did not start yet. We can see that the maximum fragments are smaller than the normal A4 paper. Such fine fragmentation was seldom found in the ordinary rings or reference rings in the mine. Note that we did not increase the explosive charge in each hole in the double-primer placement, i.e. the borehole plans were not changed at all. As a comparison, the muckpile from one reference ring is shown in Fig. 8b.

5.3. Ore flow and dilution

Due to improved fragmentation in the double-primer rings, ore flow became better and dilution was low in several rings, as shown in Fig. 9, where dilution is only 11% and 8%, respectively. From Fig. 9b we see that the ore recovery is up to 147%, meaning that at least 47% of the recovery is from one or more rings above ring 496-r24. The major reason is that average sizes of fragments in the double-primer ring became smaller, resulting in the remained ore over this ring could flow down.

5.4. Ore recovery

Table 1 shows the results for ore extraction and ore recovery from all of test and reference rings. A total of 17 rings were blasted in the reference drift 493. In test drift 496, a total of 14 DRB rings and 5 double-primer rings were tested. The results for ore extraction and recovery are shown in Fig. 10a, indicating both extraction and recovery in the double-primer rings are higher than that in either reference or DRB rings.

6. Discussion

6.1. Rock fracture and fragmentation

As mentioned previously, the fragmentation from the double-primer rings often looks fine according to our field observations. The major reason is that the double-primer placement shortens the total detonation time, and largely increases the final stresses in rock. These make the total detonation energy highly concentrated in a shorter time and with higher amplitude, compared with a single-primer placement. As a result, rock mass is highly shattered in the double-primer placement.

On the other hand, one may inquire what role loading rate may play in the double-primer placement. It is no doubt that the loading rate in the double-primer placement is higher than that in a single-primer case, since detonation time is largely shortened. It is also known that fracture toughness, compressive strength and tensile strength of rock increase markedly with increasing loading.
rate under dynamic loads \([12–16]\), indicating rock is stronger in higher loading rate. However, although rock becomes stronger or more difficult to fracture, the sizes of fragments produced decrease with increasing loading rate under dynamic loading condition \([15,17]\), and the internal cracks produced increase with increasing loading rate, too \([18]\). Therefore, a higher loading rate in dynamic loading condition is favorable to rock fragmentation, if the effect of loading rate on energy efficiency is not considered in blasting.

A good fragmentation, i.e. smaller average sizes of fragments, can delay the moving down of the waste rock above the ring in loading and therefore increase ore recovery and reduce dilution, according to previous tests in the mine \([1,20]\). In addition, a good fragmentation can save a significant amount of energy in downstream operations such as crushing and grinding. Furthermore, a good fragmentation can increase extraction speed or productivity, according to production tests \([19,20]\). In this direction, it is better to measure or evaluate fragmentation and follow up loading operation in the double-primer rings in the future.

### 6.2. On rock fracture in roofs

It has been proved that the double-primer method can efficiently reduce rock fracture in a drift roof or eyebrow break in sublevel caving, according to not only the tests in this study but also the previous tests \([7]\). Therefore, the double-primer method can be certainly used to reduce eyebrow break or rock fracture in a drift roof.

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6.3. Special phenomena

During the tests for the double-primer method, some special phenomena were found. The first phenomenon is that sometimes when fragmentation is good, ore recovery is not. For example, two rings 499–r24 and 499–r25 showed a very good fragmentation, as shown in Fig. 8a. However, the ore recovery in both rings is not good, as shown in Fig. 11 and Table 1. Fig. 11 indicates that after 10% of extraction, a great amount of waste rock must have come down. The major reason is that as ring 499-r24 was charged, a fault was found after 499-r25. The fault slid toward the hanging wall, as shown in Fig. 12 in which the left side is toward hanging wall. During blasting in the two rings, the fault might slide a certain distance to the hanging wall. This movement pushed ore fragments forward and reduced the width of ore flow in horizontal direction. In this case, if loading continues, there must be much more waste rock coming out. From Fig. 11 we can see that the iron content is only about 40% after extraction is over 10%, indicating that a great amount of waste rock has been loaded out. A similar result is found in ring 499-r24, i.e. dilution is also high. In this case, a special blast plan is to be developed in the future.

The second phenomenon is that the ore extraction was stopped incorrectly in a number of rings (particularly in many DRB rings), as shown in Fig. 9, although the extraction and recovery are already high. A common character is that a suddenly hanging up is formed by several boulders that block the draw point. In this case, especially as iron content is still very high, extraction should continue, for example, by breaking down the hanging up. Otherwise, ore loss will be unnecessarily increased.

Another phenomenon from DRB rings is that fragmentation often looked fine and the loading in the first 30% extraction was almost no waste rock. However, from about 30% (sometimes 40%) extraction there were usually some waste boulders came down. A possible reason is that the short delay times (10 ms in upper holes and 20–60 ms in lower ones) between two neighboring holes might give rise to a too strong fragment throw, making the waste rock boulders dropping down during the throw. This phenomenon is worthy of being considered in a further study on the double-primer placement since we are not sure whether 80 ms is or not the optimum delay time used in this study, at least in theory.

6.4. Ore recovery with double-primer placement

As reported in [7], the ore recovery was increased by 3% in fourteen double-primer rings (average recovery 97%) by using NONEL detonators in Malmberget mine, compared with that in seventeen ordinary rings (average recovery 94%).
In this study, the results for test drift 496 and reference drift 493 showed that the ore recovery was 108%, 76.1%, and 82.1% from the double-primer rings, reference rings, and the DRB rings, respectively. Similarly, for test drift 499 and reference drift 502, the recovery was 99.4%, 89.1%, and 73.2% from the double-primer rings, reference rings, and the DRB rings, respectively. On average, the double-primer placement shows more than 10% ore recovery than either of the other methods.

We note that the ore recovery in the last few rings in either reference drifts or test ones is high, compared with that in other places. This is because these rings are located close to the foot wall where it is easy for the remained ore in upper levels to move down during loading. Considering this situation, let us compare the recovery from all of the double-primer rings and corresponding reference rings. We consider five last rings in reference drift 493 and seven last rings in reference drift 502, so the total reference rings are twelve. We take away one ring AL502-r25 with maximum recovery and another ring AL493-r18 with least recovery from these twelve reference rings. At the same time, we take away one double-primer ring AL499-r26 with maximum recovery and one ring AL499-r25 with least recovery from twelve double-primer rings. Then the result is that the average recovery from 10 double-primer rings is 97.3% and that from 10 reference rings is 95.7%, indicating a small increase in the recovery of the double-primer rings. This result does not consider the negative effect of the fault on the recovery of double-primer ring AL499-r25, as discussed above. Anyway, although the ore recovery from the double-primer rings is increased to a certain extent, a further study on a large quantity of double-primer rings is necessary in the future since the number of the double-primer rings in this study is still small, only twelve rings.

6.5. High stresses in structures nearby and high vibrations in far-field

As shown in Fig. 4, the shock collision induced high stress wave in the half-circle with radius OD1 will completely propagate into the rock mass behind the blasting ring (right side of picture). As analyzed in Sections 2 and 3, the maximum stress in this wave can be up to more than double of the peak stress from a single primer placement. If this wave is very strong, a possible damage in the rock structures nearby and very high vibrations in the far-field may be caused. After that moment, as shown in Fig. 4, the reflected waves will immediately follow the collision-induced compressive waves, i.e. a superposition between the compressive waves and the tensile waves (reflected ones) may happen. At the same time, rock fracture occurs and the extending cracks interact with the stress waves in the collision-affected region. These of course consume wave energy. As a consequence, the waves going into the surrounding rock mass in the near or far field will be reduced more or less. In addition, approximately, the blasting-induced stress waves are a spherical wave the geometrical attenuation of which is great, i.e. with increasing distance the amplitude of the wave decreases fast. Thus, it is possible that more detonation energy might be well consumed in shattering the rock mass surrounding the primers in the double-primer case, while less detonation energy could be transported to the rock structures nearby or the far-field.

For the nearby rock structures, the maximum vibration induced by the double-primer placement could be more than double of that caused by a single-primer placement. But in sublevel caving the nearby rock structures are the production drifts. A two times high vibration might not seriously undermine the safety of the drifts. In Malmberget mine, since year 2006 a total of thirty-seven double-primer rings have been tried in different ore bodies, but no any evident rock damage in the drifts has been found, as seen in Fig. 7a. Therefore, for underground mining, especially sublevel caving, the double-primer method would not cause a marked damage to the nearby rock structures. But when this method is used in other engineering projects, for example in the case of a weak nearby structure, it cannot be excluded that the double-primer placement may cause damage in the structure. Therefore, a careful blast design together with some measurements, for example, on vibrations is necessary. Even for the future study and tests on the double-primer placement in sublevel caving some measurements and deeper theoretical studies are recommended.

For the vibrations in the far-field, the double-primer method could cause a very high vibration. In this study, the test area is much far from the Malmberget city, so the blast-induced vibrations in the city never cause any problems. But in the mine, one production area named Johannes is the nearest one to the city. Considering this situation, the double-primer method has been never tried in Johannes. However, when two middle holes in a ring were simultaneously initiated or two rings from two different drifts in the same ore body were initiated at the same time, a nearly two-time high vibration was monitored in the city, compared with the normal blasting when one hole or one ring is initiated at each time [9]. Therefore, in this case or a case similar to this, the double-primer method is not recommended. Otherwise, if this method is needed to be tried, some pre-tests and relevant measurements are necessary.

6.6. Comments on the double-primer placement

The double-primer placement has been proved to be successful in reducing eyebrow break, improving rock fragmentation and increasing ore recovery in the Malmberget mine. So far we have not found any negative effects of this method on mining production and safety. Since the double-primer rings tested in this study are not many and no measurement on fragmentation and blast parameters was done due to limited research resource during this study, more tests with relevant measurements are necessary.

In sublevel caving or other similar situation, the delay time between neighboring holes needs to be carefully chosen. A very short delay time may not produce a high ore extraction and recovery, even though fragmentation is good, according to the DRB test (some blastholes in the lower part of ring also have double-primers) in this study. The reason is that a too short delay time may give rise to a strong fragment throw and compaction to the materials (mostly waste rock) in the front of the blasting ring. As a consequence, this may cause the waste rock above the ring to drop down during the throw. In addition, this may make ore flow become worse. Therefore, a study on the relation between ore flow and blast parameters such as delay time and primer placement is needed in the future.

7. Conclusions

The double-primer placement based on shock wave collision theory is successful in reducing eyebrow break and rock break in the roof of a drift, by using either electronic or NONEL detonators. By employing the double-primer placement with electronic detonators, rock fragmentation looks much finer or better according to field observations. The double-primer rings result in a certain increase in ore recovery, compared with the reference rings and the DRB rings.

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References