Optimization of Close-Range Blasting Design with Vibration-Damping and Speed-Reduction for Open-Pit Mine in an Arid Region

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Abstract. Based on many years of on-site work experience and analysis of the impacts of heterogeneous rock mass structure, rock joints and fissure on blasting in arid regions, it is recognized that deep-hole blasting of heterogeneous rock mass will cause vibration damage to ground building structures. In addition to the influence of lithological structure, it should also take into consideration the distance variations between the location of the blast and the ground building structures. Designing an optimized blasting scheme with shock-absorption and velocity-reduction, together with safe and suitable key blasting technologies for heterogeneous rock, is core to address the safety issues of blasting vibration impact on ground building structures. For this reason, taking the blasting vibration of the second mining area of Mulei Kaiyuan Open-pit Coal Mine as an example, through survey and analysis of the seismic standards of ground buildings, operating environment and geological conditions of the blasting area, an optimized blasting network is proposed. This network involves a key technology that combines multiple blasting unit forms aiming at the realization of unit-dosage multi-stage millisecond blasting of whole or layered interval detonation. The optimized design offers five types of shock-absorption and velocity-reduction multi-stage millisecond denotation networks based on different blasting distances. Together with open-pit coal mine blasting technology, this design can effectively solve the safety issues of close-range blasting vibration on ground building structures.

1. Research Background
In an environment with arid climate, the fragmented structures of the overburdens in most open-pit coal mines are affected by drought, wind erosion and mechanical stripping, resulting in side slope made of heterogeneous rock mass structure. This can introduce huge safety hazards to blasting operation in deep concave open-pit coal mines, side-slope management and stabilization [1]. For geotechnical blasting, it is to study the energy utilization and distribution after the explosives have exploded in the geomaterial [2], i.e., to study the propagation of shock waves, stress waves, and seismic waves in the geomaterial resulted from the explosion of the explosives, and the subsequent destruction patterns of the rock media [3]. Internationally, there have been relatively systematic studies of side-slope stability technology management and homogeneous rock mass blasting theory in deep concave open-pit coal mines. Different scholars have proposed various blasting hypotheses or theories [4, 5]. For example, there was initially the damage hypothesis proposed to overcome the gravity and friction of rocks followed by the free surface and minimum resistance line theory, blasting fluid mechanics theory, maximum compressional stress, shear stress, tensile stress strength theory,
shock wave and stress wave theory, reflected wave stretching theory, quasi-static wedge pressure of detonation gas theory, stress wave and detonation gas collective effect theory, and blasting fracture mechanic theory, etc. [6, 7]. Most of these theoretical views regard the blasting target as a continuous and uniform medium, which deviates from the actual situation [8], hence further research and exploration are needed.

1.1. Blasting Area Environmental Analysis
Mulei Kaiyuan Open-pit Coal Mine, located at 110km east of Qitai County, Changji Prefecture, Xinjiang Autonomous Territory, China, is an officially registered open-pit coal mine that is in active production. At the end of 2018, the first mining area was closed, and the second mining area is still in operation. Near the second mining site, within 100m of the southern boundary of the active mine, there are several ground building structures. The nearest buildings are the automobile repair shop and engineering machinery repair shop, 86m apart from each other in the east-west direction, are less than 50 and 80m away from the blasting site, respectively. The further away store is also within less than 100m range from the blasting site. These ground buildings are mostly brick-concrete semi-temporary individual structures scattered over the terrain without unified planning. The ground elevation of the buildings is at about the same level as the blasting site.

1.2. Blasting Operation Plan
During the stripping operation north to south, the coarse sandstone with heterogeneous structure is completely exposed, and drilling rigs are needed for deep-hole blasting. Large-area deep-hole blasting with continuous bulk coupling centralized charge and multiple rows of deep holes is used on site. For the main line of blasting, the detonator and the blasthole are connected vertically. The detonator exploder ignites the No 2 rock emulsion explosives, and the detonation between the rows is ignited with multi-stage millisecond blasting. For an 8-10 m step, 10 blasting holes are used for a single-unit blast with a detonation charge of 403-720 kg.

1.3. Issues of Blasting Techniques
According to the on-site shock and the survey and analysis of the ground building quality, the vibration of the open-air blasting operation is obvious, cracks appear on the walls of the ground buildings, and there are great hidden dangers to the safety of the buildings.
   (1) The coupled continuous centralized charge used is similar to a spherical charge package. The blasting effect is concentrated on the bottom of the blasthole. The vibration attenuation is not affected by surficial changes, shallow joints and fissures. The blasting vibration on the equal level is big.
   (2) The unit explosive charge dosage and the charge density of the blasthole are relatively large, making the explosive energy too concentrated. The neighbouring coefficient of the blasthole is relatively small, making the blasting energy caused by the formation of cracks between the holes discharge earlier, and the blasting energy is not fully utilized to affect the crushing effect.

2. Analysis of Lithology Condition and Blasting Effect
(1) The mining area is arid, lack of rain and wind, the joints and fissures of the rock mass are more heterogeneous. The vertical waves in their internal propagation process are larger than the vibration energy and particle velocity absorbed by relatively homogeneous rock mass, with slower propagation speed, longer cycle, and easier to decay and weaken quickly. Therefore, the anti-vibration capability of the exposed heterogeneous rock mass will be weaker. When close-range blasting occurs, blasting vibration will have a destructive effect on the ground buildings above the rock mass.
   (2) Deep-hole blasting in open pit mines is based on the shockwave from the rock mass and compressional stress wave formed by the shockwave incident on the rock body and the scattering of the explosives and the breaking effect of the blasting gas on the rock body, because the peak value of the compressional stress wave decreases sharply as the distance from the surface of the charge to the wall of the blasthole increases. For non-homogeneous rock mass blasting, using small package
uncoupled charge, its dynamic stress field is axisymmetric, which can make the stress waves superimpose on each other, and the blasting energy is evenly distributed in the rock mass, reducing the fragmentation effect of stress wave on the rock wall.

3) The strength of the reflected wave is related to the difference between the wave impedance of the weak surface and the rock mass. Puffed ammonium nitrate explosive with a wave impedance similar to the bedrock is used as an industrial explosive to increase the breaking effect of the explosive gas on the rock. The blasting tube detonation network reduces the speed of detonation material transmission, reduces the number of detonation holes and the amount of detonation charge dosage per unit, prolongs the initiation time in milliseconds, and weakens the blasting vibration.

3. Blasting Technical Solutions

3.1. Blasting Parameters

The design uses small uncoupled explosive packages with multi-stage or continuous centralized charging. The uncoupling coefficient is 1.25, the density of the explosive package is 950kg/m³, the upper part of the charge is 40% of the charge of the blast hole, and the lower part of the charge is 60%, the unit consumption of explosive is 0.36 kg/m³. The blasting parameters of the design are listed in table 1.

| Type                      | Unit | Step height |
|---------------------------|------|-------------|
|                           |      | 10 m | 8 m | 5 m |
| Hole spacing              | m    | 5    | 4.5 | 3.5 |
| Line spacing              | m    | 4    | 3.5 | 2.2 |
| Hole depth                | m    | 2    | 1   | 0.2 |
| Step slope angle          | °     | 75   | 75  | 75  |
| Borehole explosive load   | kg   | 72   | 45.4| 13.8|
| Upper explosive column    | Kg   | 28.8 | 18.2|      |
| Lower explosive column    | kg   | 43.2 | 27.2|      |

3.2. Number of Blasthole Calculation

(1) Reinforced concrete buildings or structures without residual deformation during construction and without earthquake resistance are calculated according to the vibration resistance standards for Class II buildings, which allows for ground vibration speed of 2-3 cm/s [9, 10].

(2) Blasting is calculated according to standard funnel, medium-joint hard rock $f = 5-7$.

(3) Equation for blasting impact distance calculation:

$$R_s = \left(\frac{K}{V}\right)^{1/\alpha} Q^n$$

where $R_s$-blasting safety distance, m; $V$-vibration speed at safety range, value 2.5 cm/s; $Q$-maximum primary dose for instant or segmental initiation, kg; $m$-dose Index, 1/3; $K$-coefficient, value range 150-250, design default 200; $\alpha$-coefficient, value range 1.5-1.8, design default 1.65.

According to the three selected ground surface adjacent measuring points and different distances from the positive free surface of the blast area, the calculation of the unit detonation charge dosage and the number of primary detonation holes can be seen in table 2.

3.3. Blasting Technical Requirements

(1) According to the different blasting distances of the three measurement points in the blasting area, the amount of detonator initiation of the non-conductive detonator at the same stage is the unit detonation charge of the designed blasting network.

(2) For the 8-10 m blasting steps of the stripping operation, the design requires at least one lateral
free surface and a positive free surface, and no fewer than 6 holes per row in the direction of the parallel positive free surface.

Table 2. Number of blast holes and dose.

| Detonation distance | $Q = \sqrt[3]{R_i / \{K / V\}^{1/3}}$ (kg) | Number of blast holes |
|---------------------|------------------------------------------|-----------------------|
| 104 m               | 390                                      | 5  8  28              |
| 81 m                | 183                                      | 2  4  13              |
| 52 m                | 48                                       | 1  3                  |

(3) For the 5 m blasting steps excavated into the trench or the layered trench, two steps are grouped together and detonated by layer, with the upper and lower layered steps each having two free surfaces.

(4) Due to the unevenness of the delay interval of the detonator and continuation of post-blast stress, the stress after the explosion and the delay interval of the detonator, the time interval of the detonator and the exploder is set at 25 ms.

4. Blasting Network Design

The design uses non-conductive detonator plus “4-way” blasting network connection [11, 12] non-conductive detonator exploder + emulsified detonator + expanded ammonium nitrate explosive segmented unit dosage millisecond interval [12, 13].

4.1. 10m Blasting Step Network Design

In order to ensure the safety of the blasting network and avoid the rock mass moving faster than the blasting transmission speed of the blasting network, the in-hole explosive column adopts the 15-17 section detonator to delay the simultaneous initiation of the detonator by 350-400 ms, with uncoupling segmented charging, and 2m padded interval between the upper and lower columns.

(1) At the 104 m detonation area, unit detonation charge is 360 kg, drilling 5 rows of holes, 5 blastholes in the same segment connected by V-shaped blasting holes make one detonation unit. There is a 75 ms differential time interval between segmented detonation units. Within the hole, a 17-stage detonator exploder is used to delay the detonation (figure 1a).

(2) At the 104 m detonation area, unit detonating charge is at 144 kg, drilling 4 rows of holes, 2 blasting holes in the same segment connected by small oblique lines. There is a 25 ms differential time interval between the small oblique segmented detonation units. Between 2 detonation units, there is a 50 ms differential interval for detonation. Within the hole, a 15-section shock-conducting tube detonator is used to delay the detonation (figure 1b).

4.2. 8 m Blasting Step Network Design

Inside the hole, 13 detonators with 300 ms delay are used to initiate the detonation at the same time. There is 1.5 m spacing between the charge columns, and the space is filled, uncoupling segmented charge loading.

(1) The 81 m detonation area, unit detonating charge is at 181.6 kg, designed to have 4 rows of holes, slanting line connecting 4 blasting holes of the same segment formulating one detonation unit. Between each detonating unit, there is a 50 ms differential time interval for detonation (figure 2a).

(2) The 52 m detonation area, unit detonating charge is at 45.4 kg, designed to have 2 rows of holes, slanting line connecting 2 blastholes which will be detonated sequentially, to achieve interval detonation between the slanting holes and horizontal at 25 ms and 50 ms differential time interval (figure 2b).
4.3. 5 m Blasting Step Network Design
For the 52 m detonation area, at the temporarily formed 5 m detonating steps from the stripping work face or new horizontal mining preparation with layered trenching, digging and expansion operation, two 5 m steps are made into one group for layered extraction. Drill 3 rows of holes at each sub-step, uncoupling continuous centralized charge loading, with 3 holes forming a single detonating unit, unit detonating charge is 41.4 kg.

![Diagram](image1)

**Figure 1.** (a) V-shaped line-connected blasthole millisecond differential blasting network; (b) Millisecond differential blasting network of small slash initiation unit.

![Diagram](image2)

**Figure 2.** (a) Millisecond differential blasting network of the detonating unit of the diagonal blasthole connection line; (b) Slanting line millisecond differential blasting network.
(1) The blastholes are arranged diagonally on the lower sub-step, and the V-shaped holes are arranged on the upper step. The detonation points are located on the top lines of the positive and lateral free surfaces of the step respectively.

(2) Between the upper and lower sub-steps, unit dosages are separated at 25 ms differential interval for alternated detonation. For detonation units at different segments on the same level, the detonation interval is 50 ms differential (figure 3). The time intervals of unit detonation at different segments are listed in table 3.

![Figure 3. Slanted V-type millisecond micro-differential layer blasting network.](image)

**Table 3. Time intervals of detonation units at different segments.**

| Time interval               | Unit   | Step height |
|----------------------------|--------|-------------|
|                            |        | 10 m  | 8 m   | 5 m   |
| V-shaped holes              | ms     | 75    | 50    |
| Small slant-line holes      | ms     | 25    |
| Slant-line holes            | ms     |        |
| Slant-line alternating holes| ms     | 50    | 50    |
| Layered slant-line V-shaped | ms     | 25.50  |

5. Blasting Design Optimization

5.1. Key Blasting Technology of Vibration-Damping and Speed Reduction

(1) When blasting distance is fixed, the segmented maximum unit detonating charge can directly affect the blasting effect. By controlling the unit detonating charge (table 4), it reduces the shallow surface vibration from elastic waves induced by the conversion of part of the energy released from the explosion in the detonation process due to the reduction of the explosive charge, while at the same time keeping the amount of the staged charge constant but increasing the number of stages, or increasing blasting quantity without increasing the blasting vibration intensity. According to on-site measurements of the blasting vibration data (table 5), the measured maximum blasting vibration speed did not exceed the required value of 2 cm/s.

**Table 4. Comparison of unit explosive charge.**

| Detonation distance (m) | Designed explosive dosage (kg) | Actual charge dosage (kg) |
|-------------------------|--------------------------------|---------------------------|
|                         |                                | 10 m   | 8 m   | 5 m   |
| 104                     | 390                            | 360    | 363.2 | 386.4 |
| 81                      | 183                            | 144    | 181.6 | 179.4 |
| 52                      | 48                             | 45.4   | 41.4  |
Table 5. Blasting vibration monitoring.

| Burst distance (m) | Unit detonating charge (kg) | Maximum acceleration (cm/s²) | Maximum velocity (cm/s) | Frequency (Hz) | Duration (s) |
|-------------------|----------------------------|-----------------------------|-------------------------|----------------|-------------|
|                   |                            | Vertical | Radial | Tangential | Vertical | Radial | Tangential | Vertical | Radial | Tangential | Vertical | Radial | Tangential |
| 52                | 48                         | 24.5     | 35.0   | 31.2      | 0.82     | 0.60   | 0.70      | 42.1     | 35.7   | 36.7      | 0.32     | 0.35   | 0.31      |
| 81                | 183                        | 19.6     | 31.0   | 29.9      | 0.59     | 0.51   | 0.54      | 37.7     | 36.8   | 36.9      | 0.58     | 0.65   | 0.62      |
| 104               | 390                        | 17.5     | 22.0   | 20.2      | 0.35     | 0.32   | 0.33      | 32.3     | 30.6   | 29.6      | 0.74     | 0.87   | 0.71      |

(2) For heterogeneous rock mass, the million second time interval should be greater than the duration of elastic vibration and less than or equal to the time when the rock starts to move. The appropriate time interval of millisecond should be the most optimal to ensure that later detonation package group explodes after the earlier detonation package group. It is the best scenario when the rocks have just started to fracture but have not been blasted out. If the time interval is too short, it will turn into instantaneous blast, which cannot cause the vibration waves resulted from the before and after deep-hole detonations to interfere with each other hence to increase the vibration damage.

(3) The non-coupling charge structure is used to make the blasthole to have annular gaps along the periphery of the charge rolls. Gaps are preserved along the axis of the blasthole to reduce the peak pressure caused by the shock wave against wall of the blasthole. This will make the charge dosage to distribute evenly along the longer axis of the hole direction, thereby reducing the blasting vibration strength and shortening the blasting elastic vibration time.

(4) Increase the free surface of blasting, change and diffuse the propagation direction of the longitudinal wave, so that the energy is scattered around. On the contrary, the free surface of blasting is reduced, and the rear blast hole is subject to a large clamping effect due to the small number of free surfaces, so that the explosion stress waves are superimposed on each other, resulting in a state of extremely high stress and increased vibration damage. The results of the study show that [12, 13], from the explosion of the cartridge to the movement of the rock, each additional blast lateral free surface increases the duration of elastic vibration in the rock by 3.9 to 51 ms. The blasting vibration monitoring data can be seen in table 5.

5.2. Optimizing Blasting Network Design with Vibration Damping and Speed Reduction

(1) The detonation point is located at the lateral free surface on top of the step slope, the detonation explosion propagates in parallel with the direction of the positive free surface, so as to prevent the blasting effect from being concentrated in the main direction of the temporary ground building structures.

(2) It is preferable to select modifiable V-shaped or slant blasthole unit charge blasting networking that can achieve multi-stage millisecond micro-differential, multiple combinations of detonation unit forms and variable blasthole connection lines, to determine the millisecond micro-differential time interval through comparison. The design adopts a non-conducting detonator and “4-way” unit dosage segmented millisecond micro-differential whole layer or layered interval detonation technology to achieve multi-level unit dosage millisecond micro-differential interval detonation.

5.3. Blasting Technical Parameter Optimization for Vibration Damping and Velocity Reduction

(1) When the number of detonation holes and the amount of unit detonation charge dosage are the same, the design should choose a V-shaped blasting detonation network to cause the blasting to generate more lateral free surfaces than the slant line hole detonation network. When arranging multiple-row blastholes on the blasting steps, drill 3-5 rows of holes, and make sure to give priority to meeting the design requirements of the V-type blasthole unit dose blasting network.

(2) For situations with relatively large number of blastholes and heavy detonation charge dosage,
the segmented time interval between detonations should be no less than 75ms, to extend the propagation of the vibration wave, generated by the unit detonation charge, in the rock and to avoid the superimposition of stress waves. If the number of detonating holes is small, a 25ms detonating interval can be selected.

(3) If the chosen neighbouring coefficient of the blasthole is too big, the rock around the blasthole will have a stress reduction zone and a non-tensile stress zone, which will cause large blasting chunks. By using relatively small hole distance, the blasting energy caused by the formation of cracks between holes will discharge earlier, without allowing the full usage of the blasting energy, hence reducing the crushing effect. According to different blasting design networks, the distance between blastholes should be at 1.25-1.59 in order to reduce the action range of the stress reduction zone and the non-tensile stress zone. Table 6 lists the optimal blasting parameters and their recommended values.

### Table 6. Optimized blasting technical parameters.

| Comparative parameters      | Unit       | V-Shape Blasthole blasting network | Slant blasthole blasting network | V-shape, slant blasthole layered blasting network |
|-----------------------------|------------|----------------------------------|---------------------------------|-----------------------------------------------|
| Blasting lateral free surface | 3          | 2                                | 2.3                             |
| Unit detonating charge interval | ms         | 75                               | 25-50                           | 25                                            |
| Blasthole proximity coefficient | 1.25       | 1.29                             | 1.59                            |
| Explosive charge structure  | Uncoupled segment | Uncoupled segment | Uncoupled continuous |

6. Conclusion

(1) Close-range blasting in open-pit mine, the duration of ground vibration is relative short, usually within the range of 0.1-1.5 s, with high vibration frequency and fast attenuation, which can be regarded as pulsation or instantaneous vibration. Blast distance and the amount of explosive play a pronounced role in controlling the magnitude of the vibration. Because blasting vibration is an external load, the rock hardness and integrity in the blast area will have different effects on the blasting vibration. According to the conditions of blasting operation, the closer the blast area is to the ground building structure, the more the number of blastholes per shot, and the larger the unit detonating dosage, the shorter the millisecond interval between the unit dosage and the greater the blasting vibration.

(2) The design uses a variety of connection combination methods of non-conductive detonator plus “4-way” blastholes; it is an optimal design of blasting network and focus of research. Employing multi-stage segmented unit dosage millisecond denotation is the research content. Choosing low-yield puffing among explosive, uncoupling segmented or continuous centralized charging, selecting suitable millisecond micro-differential time interval, it can effectively disperse blasting energy and reduce blasting vibration intensity, reduce the damage to ground buildings by detonation wave. By avoiding blasting effect concentration in the direction of ground building structures, it can achieve the objectives of vibration damping and speed reduction.

Reference

[1] Chu H, Yang X, Liang W, et al. 2011 Experimental study on the blast damage law of the simulated coal. *Journal of Mining & Safety Engineering* (03) 488-492.

[2] Chen J, Gao W and Tao L 2006 Theory of rock blasting control in geology engineering *Journal of Engineering Geology* (05) 616-619.

[3] Ren Y, Cai Q, Shu J, et al. 2014 Influence of blasting vibration and structural plane progressive failure on slope stability *Journal of Mining & Safety Engineering* (03) 435-440.
[4] Donzé F V, Bouchez J and Magnier S A 1997 Modeling fractures in rock blasting *International Journal of Rock Mechanics & Mining Sciences* 34 (8) 1153-1163.

[5] Kirsanov A K, Volkmin S A and Kurchin G S 2016 A brief history of the development of blasting and the modern theory of rock breaking *Journal of Degraded & Mining Lands Management* 3 (4) 617-623.

[6] He X and Zhou C 2005 Research progression in blasting theory for fracture rock mass *Journal of Benxi College of Metallurgy* (04) 1-5+7.

[7] Xi-Bing L I, Zhang Y P, Liu Z X, et al. 2005 Wavelet analysis and Hilbert-Huang transform of blasting vibration signal *Explosion & Shock Waves* 25 (6) 528-535.

[8] Zhao J X, Liu M and Li F 2015 The study on safety management of drilling-blasting metro station construction based on OWA operator and gray theory *Applied Mechanics & Materials* (744-746) 997-1000.

[9] Wang X 2011 Blasting Design and Construction (Metallurgical Industry Press) pp 171-177.

[10] Chen Y, Chang Z and Zhao F 2017 Non-structural fracture blasting technique and case study of open pit coal mine in arid area *Journal of Mining & Safety Engineering* 34 (6) 1162-1168.

[11] Chen Y, Chang Z and Mao J 2015 Blasting effect analysis of hole-by-hole millisecond minute difference initiation, network along V-Shaped oblique line *Electronic Journal of Geotechnical Engineering* 20 (13) 2533-2538.

[12] Zhong D, He L, Cao P, et al. 2016 Analysis of blasting vibration duration and optimizing of delayed time interval for millisecond blasting *Explosion and Shock Waves* 36 (05) 703-709.

[13] Chen Y 2008 Open blasting and empirical analysis (China University of Mining and Technology Press) pp 211-234.