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Safety Assessment of Blasting Shock Wave of Linear Shaped Charge using Emulsion Explosive

Zhenyang Xu[a], Xuesong Wang[a], Yuying Ning[a], Jun Yang[b], Yanning Yu[a,*]

[a]College of Mining Engineering, University of Science and Technology Liaoning, Anshan 114051, China
[b]State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
yuyanning123@foxmail.com

In the open-pit mine, the on-site mixed emulsion explosives are used to fill the energy collecting device, and the linear energy gathering and cleaving technology is used to enhance the shaped energy jet and improve the blasting efficiency. Analyse its application safety after performing shockwave safety testing. The results show that after the optimized energy-concentrating device is filled with 0.5 Kg of emulsion explosive, the power is increased to achieve the explosive blasting effect. The generation and transmission of harmful gases are greatly reduced, which is an effective way to guarantee the effect of blasting and the safety of production.

1. Introduction

The semi-mobile crushing station in the mine is highly demanding the ore rock fragment size that will enter the machine, but there are often large blocks that exceed the standard specification in size (Avchar et al., 2018) . In general, workers are required to access the crushing station or drill-and-blast on the conveyor belt. The crushing method has great difficulty in construction, low efficiency, and easily damages to the machine parts and electronic equipment during blasting.

Today, in the rock blasting process, the linear shaped charge has been widely applied in directional fracture blasting of rocks since it features strong penetrability, rapid effect and convenient carrying (Shi et al., 2006; Chen et al., 2006). In the 1960s, Swedish scholars first used the linear shaped charge for rock blasting (Bjarnholt et al., 1983; Holloway et al., 1986). In fact, Russia's YKZ cutting cable is a kind of shaped charge pellet with a wide range of applications (Song et al., 1997). The limestone mine of Guizhou Aluminum Plant and the Lanjian Iron Mine of Pangang Group adopt a water-stemming shaped charge to smash the outsize ores (Dong, 1983). In order to quickly process the oversized rocks in the mobile crushers or on the conveyor belt, thelinear shaped charge splitting technology with directional control effect is applied to analyze the overpressure decay law of the linear shaped charge explosion shock wave, and calculate the safety distance of the machinery and personnel from it in production.

2. Design of linear shaped charge

Studies show that any curved or linear liner can form a shaped charge jet (Gao et al., 2013). In order to simplify the linear shaped charge structure, the industrial explosives are used for loading it, and the copper is chosen as the material for liner (Liu et al., 2004). The small apex angle of liner can increase the jet velocity and its kinetic energy. In America, most liners are designed as 42o angle; the jet mass and velocity are relatively stable between 30º-70º (Li, 2008; Du et al., 2012). The charge height must match the linear charge length and the width of the liner's nozzle. In this test, the ratio of the charge height to the width of the liner's nozzle is set less than 1.5.

The linear shaped charge structure is called a splitting bomb. The shell thickness is designed with reference to the Warhead (Evans, 1950) and the Russian YKZ (Song et al., 1997). It uses a PVC pipe with a wall thickness of 0.8 cm, OD of 11cm and ID of 10.2 cm; the height of splitting bomb is 20 cm, and has a circular cross section shell. Then the flat shape of liner is elliptical, which assures the liner to well fit the inner wall of the housing.

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The liner uses two apex angles, 45° and 60°. The oval copper cover is folded along the short axis at 45° and 60°, and a PVC shell is installed, seal up the liner's edge with inner wall of shell, as shown in Figure 1.

Figure 1: Forming model of splitting bomb

3. Analysis of splitting effect

If the daily production of the mine will not be disturbed, the splitting test is conducted on the large blocks around the Big Mecha for 4 times, among which, the 2# and 4# tests use the bomb suppression blankets, and 1# and 4# tests run for the shock wave overpressure. Select the more representative 1# and 2# tests for analysis. The parameters of the splitting bomb are listed in Table 1, and the rock parameters are given in Table 2, where q is the splitting unit consumption, namely the ratio of the splitting bomb explosive charge to the rock volume.
The test is conducted on the shock wave overpressure in the field application to analyze the splitting safety and the reliability of protection technology, and calculate the allowable safety distance for the shock wave overpressure from personnel and machinery.

Table 1: Factors in the table

No.	Apex angle /°	Explosive load /Kg	Liner thickness /mm	Liner nozzle /cm	Blast height /cm	Unit consumption /g·m^{-3}
1	60	0.5	0.3	8.2	1	0.47
2	60	0.5	0.3	8.2	3	0.24
3	45	0.5	0.3	8.8	1	0.72
4	45	0.5	0.3	8.8	2	0.6

Table 2: Factors in the table

No.	length /m	wide /m	high /m	volume /m^3
1#	1.2	1.1	0.8	1.056
2#	1.7	1.5	0.8	2.04
3#	0.9	0.7	1.1	0.693
4#	1.3	1.0	0.65	0.845

3.1 Test program

The test uses a Tektronix TDS5054B oscilloscope, a DHF-4 charge amplifier, and a piezoelectric crystal free field shock wave pressure sensor.
When the explosive charge in the open-air surface blast does not exceed 25 kg one time, the allowable safety distance of the air shock wave from the personnel can be determined according to the formula (1) (Ma et al., 2008).

$$R_S = 25\sqrt[3]{W} \tag{1}$$

Where: R_s the minimum allowable distance of the air shock wave from the person in the shelter, m;
W - Single blast equivalent of TNT explosive mass, Kg.
Under the given atmospheric pressure conditions, the TNT equivalent coefficient of the rock emulsion explosive is 0.62(Fan et al., 2011), then the TNT mass equivalent to 0.5Kg emulsion explosive is:

$$W = k_e \times m_e \approx 0.31 \tag{2}$$

Where: k_e is the TNT equivalent coefficient of the emulsion explosive; m_e is the mass of the emulsion explosive used for the single-shot test.
According to the calculation, R_s=17.6, the distance from the measured point to the explosion center can be less than 17.6 m.
The 1# and 4# tests are performed for shock wave overpressure. 4 measuring points A, B, C, and D are arranged into a straight line, where the sensors are secured by the GPS, respectively, as shown in Figure 2. 1# test is a linear splitting bomb protection-free explosion; 4# test is covered with the bomb suppression blanket for protection. Based on two shock wave data, the safety of shock wave is analyzed during splitting.

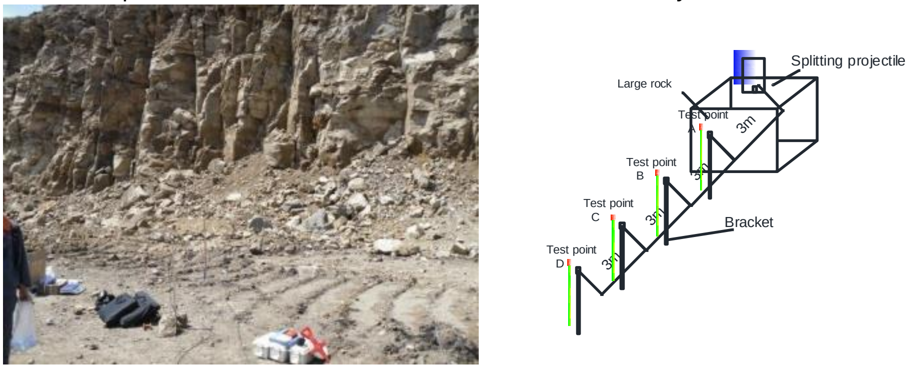

Figure 2: Layout for measuring points

3.1 Test results of shock wave overpressure

The shock wave overpressure-time history curves of each measurement point in the two tests are shown in Figure 3. It can be seen that in 2 ms after the explosion, the time-to-peaks of the four measuring points in turn lag behind with the increase of the distance.

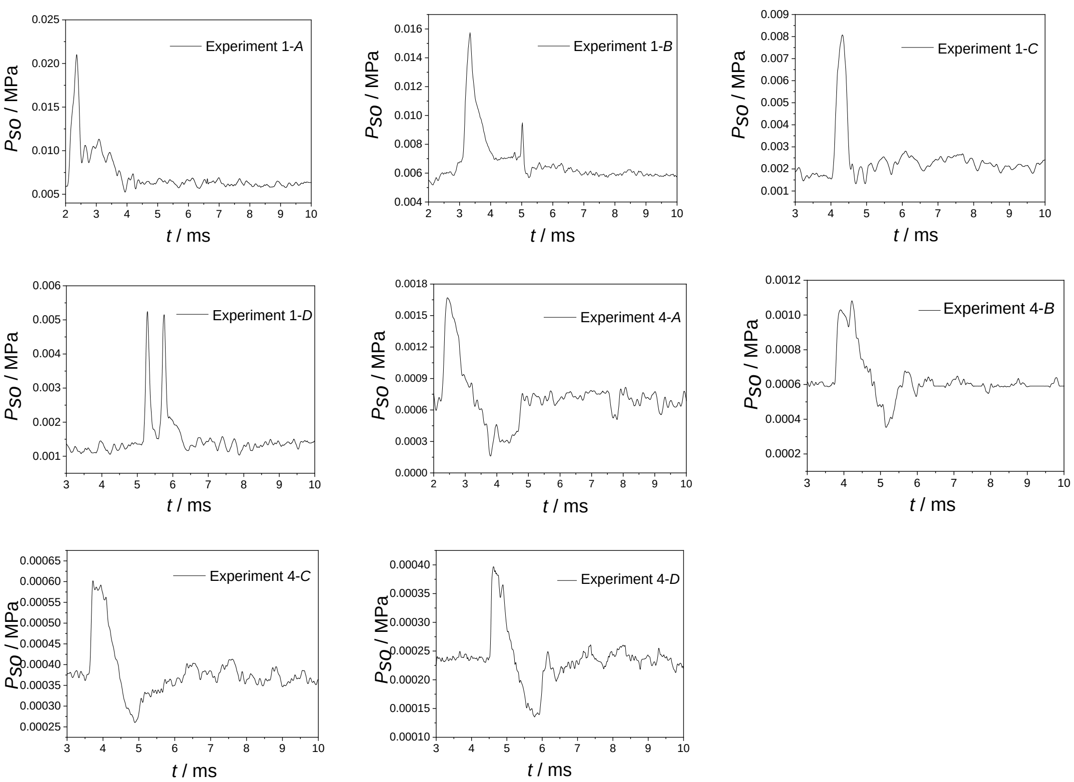

Figure 3: BP network diagram

Table 3: Factors in the table

	Point shock wave overpressure peak/MPa				Protective cover
	A/3 m	*B*/6 m	*C*/9 m	*D*/12 m	
$1^{\#}$ test/MPa	0.0212	0.0157	0.0081	0.1101	No
$4^{\#}$ test/MPa	0.0017	0.0011	0.0006	0.0004	Yes
Attenuation rate/%	92.17%	93.12%	92.59%	92.45%	

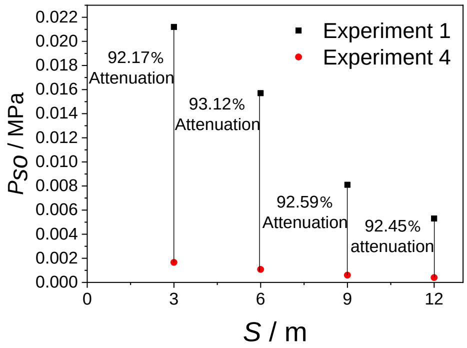

Figure 4: BP network diagram

As shown in Table 3 and Figure 4, the shock wave overpressure peaks at the four measuring points are linearly attenuated with the distance. Since the 4# test uses the protection of the bomb suppression blanket, under the given explosive load, the shock wave overpressure peaks at each measuring points weaken by 90% or above when compared with the 1# test.
The explosive is regarded as a spherical powder charge that explodes in the air free field (Jiang, 2010), and according to the formula recommended by the literature and Sadovskyii M A, the peak, Pso, of the air shock wave overpressure is obtained as follows.

$$P_{SO}=\begin{cases}\dfrac{A}{Z}+\dfrac{B}{Z^2}+\dfrac{C}{Z^3}, Z\le 1\\ \dfrac{A_1}{Z}+\dfrac{B_1}{Z^2}+\dfrac{C_1}{Z^3}, 1<Z\le 15\end{cases} \tag{3}$$

Z is the proportional explosion distance, and A, B, C, A_1, B_1, C_1 are fitting coefficients.
The proportional explosion distance Z is

$$Z=\frac{R}{W^{1/3}} \tag{4}$$

Where: R is the distance between the measuring point and the explosion source center, m; W is the explosive equivalent to TNT after conversion, Kg.
Take the calculation result of the upper section, W=0.31, and calculate the Z to determine whether data can be used to fit the one shock wave overpressure peak formula. The distances between 4 sensors as measuring points and the blast center are 3 m, 6 m, 9 m, and 12 m, respectively, and the corresponding values Z_1, Z_2, Z_3, Z_4 are

$$Z_1=3.75, Z_2=7.5, Z_3=11.25, Z_4=15 \tag{5}$$

In 1# test, the shock front pressure peaks at the four measuring points that correspond to the blast center distances are 0.0212 MPa, 0.0157 MPa, 0.0081 MPa, 0.0053 MPa, respectively, and the shock wave overpressure peak can be calculated.

$$P_{so1}=\frac{0.01}{Z}+\frac{0.0137}{Z^2}+\frac{0.078}{Z^3} \tag{6}$$

In the 4# test, the shock front pressure peaks at the four measuring points that correspond to the blast center distances are 0.00166 MPa, 0.00108 MPa, 0.0006 MPa, 0.0004 MPa, respectively, and the shock wave overpressure peak can be obtained.

$$P_{so4}=\frac{0.001}{Z}+\frac{0.0015}{Z^2}+\frac{0.003}{Z^3} \tag{7}$$

3.2 Safety analysis

If the action time is less than 2.8 ms, damage threshold for shock wave overpressure peak is 9.81 KPa (Xu, 2014; Zhu et al., 2018). At the point A of 1# test, the shock wave overpressure peak is 21.2 KPa. In this case, compared to 47.8 KPa measured at 5 m from the explosion source when 0.5 Kg TNT explodes in the air (Hu and Tang, 2014), the linear shaped charge reduces the ambient air shock wave intensity by 30%.Probability of top event of the power supply:

At the point B of 1# Test, the shock wave overpressure peak reduces to 15.7 KPa. Although it will not impair tympanic membrane of personnel, the shock wave will cause damage to some low-intensity parts such as mechanical glass. In order to simulate the working environment in the mobile crusher, objects such as glass, canvas, electronic scale, carton, bucket, etc. are placed at the measuring point C of the field. After the test, it is found that there is no damage to these objects. 1# Test point D is 12m away from explosive center, and the shock wave overpressure peak is 5.3 KPa, which basically guarantees that the mechanical equipment will not damaged and the personnel are not injured.

At 4# test point A, the shock wave overpressure peak is 1.66 KPa, lower than the injury threshold of 9.81 KPa. It can be seen here that personnel will be protected from injury of shock waves. Calculate according to the fitting formula, the injury threshold is 9.81 KPa. When the safety distance is 2.1 m, the shock wave overpressure peak is 5 KPa, which can ensure the safety of personnel and equipment. However, the safety distance allowable for the personnel should be preset as above 2.1 m due to the loud noise.

4. Features of directional control splitting technology

The former Soviet Union has made extensive studies on the bulk rocks with the shaped charge. Some mines in the Soviet Nonferrous Metals Industry have invented explosives with a considerable unit consumption of 2.7 Kg/m3. The 3KII shaped charge is loaded with the high explosive TNT, so that its safety is somewhat reduced. In particular, it has a certain pollution to the environment. The Andreifu open-pit mine of the Lenin mine company crushed the quartzite with a Protodikonov's Hardness Coefficient of 14-16 using a pressurized shaped charge. The explosive unit consumption is 0.38-0.42 Kg/m3, but the flying stone is still far away, generally 50-60 m.

In China, there are also studies that focus on smashing large blocks of rocks using the shaped charge (Luo et al., 2007).but the fruit borne by these efforts have not been applied in large-scale production and works. They focus less on the control of rock fracture morphology. Compared with the existing method of crushing the shaped charge, using the optimized energy collecting device and using the penetration of the linear jet, the explosive energy can reach the explosive explosive effect after filling the mixed emulsion explosive, and the single consumption is small and safe. Greatly improved, greatly reducing the generation and spread of harmful gases. It can realize the control of the rock splitting direction. When the splitting occurs, there is basically no explosive flying stone and explosive flying pieces, and the safety hazard range is greatly reduced.

5. Conclusion

(1) Experiments on large rocks with heterogeneous structures, using splitting bombs filled with emulsion explosives, can achieve the desired effect, low unit consumption, and change the linear jet according to the influence of rock properties on wave propagation, reflection and transmission. Penetrate the location and direction to control the development of rock splitting;

(2) When the 0.5 Kg emulsion explosive is loaded with the splitting bomb, the distribution law of the blast shock wave overpressure is analyzed. The results show that the linear shaped charge effect reduces the peripheral shock wave by more than 30%; for the unprotective splitting bomb, the safety distance of mechanical equipment is 9 m; when using the bomb suppression blanket for protection, the shock wave strength declines by about 90%; when using in large mechanical equipment, it will not cause damage to mechanical parts and electronic equipment;

(3) In the case where there is no protective equipment, the explosion safety distance when loading 0.5 Kg emulsion explosive is 12 m; in the case when there is a bomb suppression blanket, the shock wave overpressure peak is 5 KPa when the safety distance is 2.1 m, which can guarantee the personnel and equipment safety, but the impact of noise on people needs to be controlled.

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