Munroe effect based on detonation wave collision

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Abstract. Munroe effect has been more and more used in blasting engineering and most assembling energy technologies use a shaped charge device. In this paper, a new method is used to achieve detonation wave collision by detonating cord initiation system. A numerical simulation using LS-DYNA on detonation wave propagation and collision process caused by different initiation forms is implemented. Numerical results show that peak pressure by this new method can reach 2.42 times than the traditional method, and the growth of specific impulse at the explosive bottom is 49% compared to early results. Based on this numerical simulation, an experiment of explosive-determination of power be implemented, the experiment result can verify the simulation result well.

1. Introduce
Munroe effect is a phenomenon that increases the explosive damage ability by changing the direction of detonation wave propagation. This phenomenon is mainly caused by explosive superposition in the hollow cavity which comes from the use of shaped charge [1-2]. Several studies of Munroe effect are reported in the literature. At present, Munroe effect is mainly caused by metal cover shaped, such as conical, hemispherical and double conical. This effect is widely used in military, exploration and cutting. LI et al [3] applied the Mach reflection principle, to demonstrate that high detonation velocity explosive initiating low detonation velocity explosive can enhance the detonation pressure. Wang et al [4] used meshless MPM methods to simulate the detonation wave. O.Aysisit [5] used the nonlinear dynamics software AUTODYNA to study shaped charge in the process of four different types of asymmetric defects. Baker E L et al [6] had an experiment on the selectable initiation shaped charge to show that jet output is predictable and can be varied significantly for different target. Li et al [7] applied damage mechanics and dynamic caustics transmission to study the crack direction of rock fracture under the shaped charge and describe the physical process of the fracture. J.F. Molinari [8] analysed the formation, fragmentation, and penetration in a plate of a copper jet that develops in a shaped charge by numerical simulation. Qin [9] designed ‘double shaped groove cartridge’ to realize the Munroe effect by a shaped charge device. In this paper, a new method is used to achieve detonation wave collision by high detonation velocity explosive initiating low detonation velocity explosive. Through numerical simulation and standard test, this method can achieve the Munroe effect perfectly. Compared with the former method, this method has advantages of avoiding the shaped device, simplifying the traditional shaped charge, improving the working efficiency, reducing the blasting cost.
2. Detonation pressure increase theory

Detonation pressure increase theory is to use low detonation velocity explosive as the main charge, the high detonation velocity explosive as initiation, causing the detonation wave collision to achieve the Munroe effect. For the detonation pressure $P_H$ of the blasting bore wall, the following formula is often used:

$$P_H = \frac{1}{K+1} \rho_0 D^2$$  \hspace{1cm} (1)

Where $K$ is a constant polytropic exponent, for high detonation velocity explosive $K$ is set to 3, while for low detonation velocity explosive $K$ is set to 1.5–2.8. $\rho_0$ is the initial charge density. $D$ is the explosive detonation velocity.

For the detonating cord, the detonation pressure can reach to 13.74 GPa. However, for ANFO (Ammonium Nitrate / Fuel Oil), the pressure only reaches to 39.87% of the detonating cord. Hence, ANFO is worse than detonation cord if rock fragmentation is the only consideration. But if we use the high-energy explosive (i.e. the detonating cord) to initialize low-energy explosive (i.e. ANFO), may cause to the detonation pressure increase in the hollow cavity where high-energy explosive blast in advance.

Figure 1 shows the initial parameters of the detonation wave. As shown in Figure 1(a), the physical state (1) spread to the initial state (0) after the explosive was detonated, the whole is a continuous process, and this is the common detonation wave propagation process. However, the detonation wave reflection will happen when two detonation wave have a collision, it means that if the separate detonating cord initiation is used, the detonation wave will separate from both sides and when the spread to the center, a detonation wave collision will happen, causing the collision state (2) as shown in Figure 1(b). The collision process is satisfied with the conservation equations for mass, momentum and energy. After the collision, part of the detonation wave reflected back in the opposite direction, and the others lead to the Munroe effect.

Firstly, the detonation wave continuously spread from the initiation point when the explosive was detonated. Secondly, the detonation wave gathered in the center of the bore. Finally, the detonation wave spread to the sides along the center line, causing Mach reflection when the angle $\alpha$ reach to a certain value, with the angle’s increasing, and the detonation wave can form a trumpet-shaped area where the energy density, pressure and gas density are high. The detonation pressure of this area can
be three times than the stability detonation pressure [10]. Therefore, the destructive effect of the hole is stronger.

According to the theoretical calculation, the detonation wave reflection ratio $\beta$ and polytropic exponent $K$ follow the equation as below:

$$\beta = \frac{(5K + 1 + \sqrt{17K^2 + 2K + 1})}{4K}$$  \hspace{1cm} (2)

For a high detonation velocity explosive, $K$ is equal to 3 and the pressure ratio is 2.39 times while for a general explosive, $K$ is equal to 2 and the pressure ratio is 2.44 times.

3. Numerical simulation

3.1. Calculation model

![Figure 2. Model for numerical simulation](image)

LS-DYNA is used to simulation the detonation wave propagation and show pressure distribution images under different initiating form. Three initiating forms are chosen such as combine detonating cord, separate detonating cord, and exploder center initiation. Figure 2 is the section view of the calculation model for the present experiment (explosive-determination of power test) [11]. The diameter of lead column $\Phi=200\text{mm}$, height $h_1=200\text{mm}$, the diameter of drilling $\Phi=24.5\text{mm}$, loading height $h_2=21\text{mm}$. The FEM formulation for explosive and detonating cord is ALE (Arbitrary Lagrange Eulerian) while lead column is Lagrangian.

3.2. The simulation results and analysis

![Figure 3. In the process of the separate detonating cord initiation system](image)

Figure 3 shows the process of the separate detonating cord initiation system. At first, the detonation wave propagation along the detonating cord. When $t=15.975\mu\text{s}$, the detonating cord dies out, and the maximum detonation pressure from the detonating cord transferred to the ANFO. Then, the detonation wave spread to the center line from top to bottom. When $t=36.984\mu\text{s}$ the detonation wave collision for the first time. Whereafter, the detonation wave collision spread to the bottom of the hole. When $t=44.987\mu\text{s}$, ‘Mach reflection’ is happened and lead to a high power density, pressure and gas density
trumpet-shaped area. Finally, the ANFO die out and assembly energy spread out gradually.

Figure 4 shows the process of the combine detonating cord initiation system. Detonation wave spread to around like the model ‘inverted cone’. When the detonation wave spread to bore wall, it will continually spread along the bore wall. When $t=37.915\mu s$, the explosive dies out. Subsequently, the detonation wave reflection in the bore wall, and the collision will happen when the spread to the center line. However, the energy of the detonation wave has a great decay at the same time.

**Figure 4.** In the process of the combine detonating cord initiation system

Figure 5 shows the process of the exploder center initiation system. The detonation wave spread to the unexploded area as the form of ‘spherical’. When $t=38.945\mu s$, the explosive dies out. A high pressure region at the base of the explosive will be formed due to collision of the detonation wave. Then, the detonation wave will decay along its spreading direction.

**Figure 5.** In the process of the exploder center initiation system

**Figure 6.** Detonation pressure curve contrast

**Figure 7.** Contrast of impulse at the bottom of explosion centre
To observe the bore wall detonation wave propagation law under different initiation forms, select the stability point and the collision point, and draw the detonation pressure curve as shown in Figure 6 (a). As can be seen from the curve, the ‘Mach reflection point’ detonation pressure in the process of the separate detonating cord initiation is up to 13.60 Gpa as 2.42 times as the stability point of the ANFO. The result is consistent with the theoretical calculation. Compare the peak detonation pressure under different initiation forms as shown in Figure 6 (a). The maximum of the separate detonating cord initiation is 19.85% more than combine, and the exploder center initiation only increases 22.7% than the stability pressure, far less than the detonating cord initiation. Therefore, the peak detonation pressure of the separate detonating cord initiation is greater than the combine, and the minimum is the exploder center initiation.

Choose the element at the bottom of the explosive center to draw the specific impulse curve as shown in Figure 7. The specific impulse of the separate detonating cord initiation is value to 1.97×10^5 Pa•s increased by 49% than the exploder center initiation. However, the combine only increased by 42% than the exploder. That is to say, the detonating cord initiation system can change the specific impulse distribution, make it increasing dramatically.

4. Lead block test
In order to verify the numerical simulation results. In this paper, 8 groups of experiments had been designed according to the lead block method (The national standard of the People’s Republic of China). The sketch of the field test is shown in Figure 8. In order to form contrast test, 2 groups of test were carried out in each initiation forming, taking the mean value making a comparison. The test results are shown in Figure 9.

![Figure 8. The photograph of experiment](image)

![Figure 9. The test result of lead block method](image)

We can learn from the Figure 9. Compared to the exploder center initiation system, the explosive-determination of power has the growth of 12.6% in the combine and 11.8% in the separate detonating initiation system, while the hole depth after blasting increase 55% and 80%. It shows that the detonation wave collision at the bottom of the separate detonating cord initiation system is the most intense. However, the explosive-determination of power in the separate detonating cord initiation system is slightly less than the combine. As a whole, compared to the numerical results, using the
detonating cord initiation system can produce the detonation wave collision and form Munroe effect, but different initiation forming can cause different detonation wave propagation forming.

5. Conclusion
In this paper, at first, the detonation pressure increase theory is described in the basis of the Mach reflection. What's more, a numerical analysis on the detonation wave propagation and collision process under different initiation forms using commercial explicit FEM software LS-DYNA is implemented. Finally, a standard test is used to verify the numerical results. On the whole, we come to the conclusions through the present study as follows:

(1) From the comparison of peak pressure, it shows that the peak pressure of the detonating cord initiation system can reach to 2.42 times than the stability pressure.

(2) From the analysis of the element specific impulse at the bottom of the explosive, the separate and the combine initiation system respectively increases 49% and 42% than the tradition. It is preliminarily proved that the detonating cord initiation system can increase the specific impulse at the bottom of the explosive.

(3) From the results of explosive-determination power experiment, the detonating cord initiation system can do 12% more work than traditional initiation system. It can indicate that the detonation wave collision can improve the effect of blasting.

(4) Using the high velocity detonating cord initiation the low velocity explosive ANFO can lead to Munroe effect through the detonation wave collision. Comparing with the relevant literature that using shaped device implementation Munroe effect, this method has a simple process, low cost, low labor intensity and higher work efficiency.

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