Optimal tests of slotted cartridge device used in directional fracture blasting in roadway

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Abstract
Directional fracture blasting with slotted cartridge uses the cumulative effect of slotted seam to cut the rock in directional fracture by redistributing the energy inside the blast holes. Based on the theory of the three phases, authors established a calculation model considering three influencing factors. Open-air experiments with similar rocks were first carried out on the ground, then the slotted device, materials of slotted pipe, charge structures, blasting parameters and scheme are determined preliminary. Based on the open-air experiments and following the requirements of smooth blasting, the both-sides comparison blasting experiment of the surrounding holes and all surrounding holes of whole-section comparison blasting are conducted in roadway. It is proved that the best blasting device and charge structure is the slotted PVC pipe with one closed end. The results of application showed that the hole trace save ratio can reach more than 90% when directional fracture blasting was carried in side hole, the charge decreased 20.5% compared

with the original plan. The hole spacing was expanded from 300 mm to 450 mm. This blasting device effectively improves the smoothness of roadway surface and reduces the blasting damage of surrounding rock in cross section.

Key words: ADIRECTIONAL FRACTURE, SHAPED CHARGE BLASTING, SLOTTED CARTRIDGE, PVC PIPE, ROADWAY DRIVAGE

1. Introduction

Drilling blasting is still a main technology in hard rock roadway tunneling, when the Protodyakonov coefficient (*f*) of the solid rock is greater than 6. Due to the adverse environments of underground construction, blast-hole arrangement and charge cannot mostly be arranged strictly in accordance with design code, which often lead to serious over-break or under-break of excavation and destroy the stability of surrounding rock. Directional fracture blasting with slotted cartridge is one of the effective blasting technology, which is put forward to reduce or avoid over-break and under-break and more effectively protect the surrounding rock.

The idea that prefabricated crack in rock was used to control the cracking direction was first proposed by Foster. In the 1960s, this technology had been further development [1, 2]. The laboratory simulation experiment was executed and some effects were obtained in the field tests. Then it prompted the technology of directional fracture blasting of rock to mature. There are a variety of methods to achieve directed fracture blasting. According to the different of formation mechanism and ways of initial crack on hole wall, the directional fracture blasting method can be broadly divided into three categories: notched-hole, shaped charge and slotted cartridge [1, 2]. Fourney etc. proposed to use slotted pipe cartridge in rock blasting, so that the rock can form better [3]. Since the 1990s, directional fracture blasting technology had a rapid development and application at home and abroad. There have been made many research results in mechanism and numerical simulation, the materials of slotted pipe, the calculation and design of parameters of slotted cartridge blasting and the application of ground and underground rock blasting engineering and so on [4-16].

Directional fracture blasting with slotted cartridge can be divided into stages of explosives, the initial stage of crack formation and crack propagation stages. Non-radial coupling coefficient, kerf width and the slotted pipe material effect initial crack formation of slotted cartridge blasting. Based on the theory of the three phases, authors established a calculation model considering three influencing factors. The experiment of the ground and underground was carried out to solve the problem of over-break and under-break in the process of excavation. Materials of cutting blasting device and charge structures were optimized on the basis of predecessors' work in this paper. The blasting device and charge structure with PVC slotted pipe which was closed at one end was proved to the optimal blasting scheme. The shaped blasting devices can improve the effect of smooth blasting molding in rapid advance of roadway. The roadway or outline of tunneling can get a good molding effect and the smoothness is high. The hole trace save ratio can reach more than 90% in directional fracture blasting of side borehole of whole-section. Through the directional fracture blasting with slotted cartridge, the hole spacing was expanded from 300 mm to 450 mm, which increases more than 50%. The charge decreased 20.5%, when it was compared to the original plan.

2. Calculation model of directional fracture blasting with slotted cartridge

Directional fracture blasting with slotted cartridge is using slotted pipe structure (as shown in Fig. 1) which containing explosives into the blasting hole. In the place with no slots, detonation products directly impact the inner surface of pipe shell. Because the density of pipe shell is greater than the product on the detonation wave surface and the compressibility of pipe shell is generally less than the detonation products, then the detonation product will reflect from the inner surface of the shell and then the reflection shock wave and a small amount of transmitted wave are produced. The shock waves travel along the outside surface of the pipe shell. The transmitted wave energy is greatly reduced because of attenuation caused by the pipe shell and the annular space between the shell and the hole wall. At the same time, the shells absorb part of the energy by its deformation and displacement. Thus, the possibility of producing radial cracks on hole wall without slot is greatly reduced. Rocks at slot suffer earlier and larger explosion load, the detonation products shock air medium directly at slot, then induce shock waves and form the high speed and high pressure jet to act on the hole wall in slot direction. Which lead to the radial cracks caused by blasting rock having a priority extension at the predetermined slot area [3, 17-18]. If the impulse density of shock waves is larger than blasting rock, the rupture would be produced on the hole wall and pre-form the initial cracks. In the other direction of slot pipe, the pipe shell hinder the dispersion of detonation products and the energy flow further focus on the slotting direction, to some extent strengthen the damage of rock in slotting direction. And other direction joint outside, shell to burst from detonation of hinder the formation, so that the energy flow to further cut direction, to some extent strengthen the destructive effect of cutting direction. The characteristics of this method is not to need to weak the mechanical strength of the surrounding rock but one concentrated load was used to control the development of radial cracks in prospective area. This load was produced by special slotted pipe in the action phase of high pressure of the detonation products.

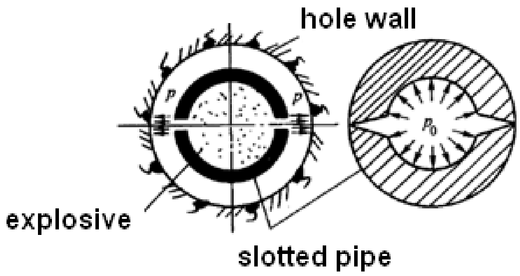


Figure 1. Principles of cutting seam cartridge blasting.

As the initial oriented crack first formed in the direction of the slit, stress relaxation is occurred in the blasting hole wall, to some extent which stops crack forming in other directions. Stress concentration appears in the initial crack tip under the action of the field of quasi-static of explosion gas and the wedge after initial oriented cracks formed. The crack will continue to expand and present brittle fracture, when its dynamic stress strength factor exceeds the dynamic fracture toughness KIC.

Directional fracture blasting with slotted cartridge can be divided into three stages: The first stage is from explosive initiation to explosive complete explosion in slotted pipe. The second stage is that the explosion shock wave out of the slit act on rock, and forming the initial crack. This stage accompanies the interaction process between detonation products and the slotted pipe wall: one is the detonation products’ transmission and reflection on pipe wall, and the other is pipe wall’s moving to the hole wall under impact action. The third stage is cracks expanding process under the detonation products promotion, at the same time, pipe wall crowd with blasting hole wall, and the slotted pipe wall is destroyed under the common actions of impact and heat produced by explosion product.

2.1 The first stage - the stage from explosive initiation to initial shock wave

The slotted usually adopts point initiation and the detonation wave front propagates in the form of spherical surface. The wave propagation direction is always perpendicular to the wave front. For cutting seam cartridge, with the constant expansion of detonation products, the initial shock wave is formed at the cutting seam which the air in contact with the explosive.

According to Landau and Sidanvkvich’s proposition that the expansion process of detonation products can be described in two isentropic equations. Therefore, the expansion process of detonation products can be divided into two phases when calculate parameters of the initial shock wave. In the first phase, the detonation products pressure P_D expands to a critical pressure P_k, and the adiabatic index is unchanged. That is to say the expansion of detonation products comply the following rules:

$$P_D v_D^k = P_k v_k^k \tag{1}$$

The second phase expansion of detonation products from pressure P_k to the initial pressure Pi, and the detonation products follow the isentropic equation of perfect gas. Follow the rules:

$$P_k v_k^\gamma = P_i v_i^\gamma \tag{2}$$

Where, k=3, γ=1.2~1.4.

According with the continuous conditions of interface, the pressure behind the shock wave and the air particle velocity can be obtained using Hugoniot equation.

2.2 The second stage—the formation stage of initial crack

The shock waves produced by explosion attenuate faster with the increase of propagation distance. The attenuation of overpressure of shock waves in the infinite air domain is calculated using empirical formula obtained from the experimental regression [7]. The peak overpressure formula of shock wave proposed by Henrych is adopted in this paper [19].

$$\Delta P=\begin{cases}\dfrac{1.40717}{Z}+\dfrac{0.55397}{Z^2}+\dfrac{0.03572}{Z^3}+\dfrac{0.000625}{Z^4} & 0.05\le Z\le 0.3\\ \dfrac{0.61938}{Z}+\dfrac{0.03262}{Z^2}+\dfrac{0.21324}{Z^3} & 0.3\le Z\le 1\\ \dfrac{0.0662}{Z}+\dfrac{0.405}{Z^2}+\dfrac{0.3288}{Z^3} & 1\le Z\le 10\end{cases} \tag{3}$$

Where, $Z=R/W^{1/3}$, R is the distance between the measuring point and explosion center (m), W is equivalent charge of TNT.

The overpressure of shock waves is related to mass of charge and the distance from the explosion center in the infinite air domain. For the slotted pipe blasting, there leave a certain gaps between slotted pipe and hole wall. The ratio of hole diameter and charge diameter is defined radial decoupling coefficient α. when the diameter of hole is fixed, the larger is α, the smaller is the charge of blasting hole per unit length [7]. Therefore, authors intend to correct the overpressure of shock wave calculated by the empirical formula through multiplying a coefficient λ.

Generally there are two failure modes of the formation of initial cracks at the hole wall with slotting seam. One is forming shear stress difference under shock wave action between rock mass at slotting seam and surrounding rock, and the initial damage of hole wall is emerged under the shear stress action. The other is forming the loop tensile stress at slotting seam because of the protective effect on the hole wall by slotted pipe. Hence, authors think that cannot simply consider the single failure mode.

Let P_b be directly pressure acting on the hole wall by explosion shock waves (through the slotting seam), and let P_i be pressure acting on the hole wall through the slotted pipe wall. The shear stress difference of hole wall at slotting seam is:

$$\tau=P_b-P_i$$
$$\tau\ge S_{ds} \tag{4}$$
$$S_{ds}=\sigma\tan\varphi+C$$

Where, S_{ds} is dynamic shear strength of rock, C is dynamic cohesive force of rock, φ is dynamic friction angle of rock.

If the tensile failure of rock at the hole wall with slotting seam occurs, the failure criterion can be established as follows:

$$\sigma>S_{dt} \tag{5}$$

Where, σ is maximum loop tensile stress acting on hole wall, S_{dt} is dynamic uniaxial tensile strength of rock.

The relationship between loop stress and radial stress is:

$$\sigma=\mu P/(1-\mu) \tag{6}$$

Where σ is Poisson's ratio of rock, P is pressure acting on hole wall.

It can be obtained by formula(5) and (6), when cracks appear under the action of loop tensile stress for single blasting hole the hole pressure P should satisfy:

$$P>(1-\mu)\cdot S_{dt}/\mu \tag{7}$$

$$P>(1\text{-}\mu)(C-\tau)/(\mu\cdot\tan\varphi) \tag{8}$$

2.3 The third stage—the initial stages of crack formation

After initial cracks formed, cracks tip continue to expand under the joint action of explosive gas and stress wave. According to the fracture mechanics theory of rock, under the action of quasi static pressure, if meet formula (9), the cracks would be initiated and expanded:

$$K_I>K_{IC} \tag{9}$$

Where, K_{IC} is dynamic fracture toughness of rock, K_I is the stress strength factor at the expanding crack tip,

$$K_I=P\eta\sqrt{\pi(r_h+a)} \tag{10}$$

Where, a is expanded length of crack, η is correction coefficient of the stress strength factor, and $\eta=\eta\ [(r_h+a)/r_h]$. Thus,

$$P\ge\frac{K_{IC}}{\eta\sqrt{\pi(r_h+a)}} \tag{11}$$

According to the elastic theory, the approximate maximum extended length of rock crack a can be got referring to the lame solution.

$$a=r_h\left[\sqrt{\frac{\mu P}{(1-\mu)S_{dt}}}-1\right] \tag{12}$$

The kerf width of slotted cartridge can affect the pre splitting occurred preferentially on the hole wall. If the kerf width is too small, then the direct dynamic action on the hole wall will be weakened. If the kerf width is too large, the dynamic action range on the hole wall will increase, the development direction of crack is difficult to effectively control. According to the fracture dynamic theory and Mohr-Coulomb strength criterion of rock fracture in Kulun, the relationship formula between the kerf width and crack length is put forward.

$$b=a/[2tg(\theta/2)] \tag{13}$$

Where, θ is the angle between oriented crack, $\theta=\pi/2-\varphi$.

When calculate maximum extended length of rock crack, in addition to considering the dynamic fracture toughness of rock and the radius of the hole and other factors, the impact time of shock wave overpressure is another main factor influencing the crack length. The duration of shock wave overpressure generally include rising duration and descending duration. Generally it is extremely difficult to carry out analytic solution of shock wave overpressure, and using the experience formula to solve the problem in practice. The impact time of shock wave overpressure in the infinite air domain is calculated using the research results of Henrych [19].

$$T_{\mathrm{a}} = 0.34R^{1.4}Q^{-0.2}/c_{\mathrm{a}}$$
$$T_{\mathrm{r}} = 0.34R^{1.4}Q^{-0.2}/c_{\mathrm{a}} \quad (14)$$
$$T_{\mathrm{d}} = 0.0005Z^{0.72}W^{0.4}$$

Where, c_{a} is the sonic speed, T_{a} is arrival time of shock wave, T_{r}, T_{d} are respectively rising and descending duration of shock wave overpressure.

The slotted pipe wall has certain strength, and it would be destroyed under the common actions of impact and heat produced by explosion product, then the wrapped function to explosion gas lost. Therefore, the influence on from material of slotted pipe is remarkable. In addition, the kerf width plays a major role in the release rate of explosive energy, and non-radial coupling coefficient α determines the charge of hole per unit length [7]. As a result, the rising duration of shock wave overpressure is much longer than the direct action time of explosive on hole wall in theory.

Above all, authors introduce an increasing coefficient of the rising duration of shock wave λ, and λ is a function includes the kerf width, non-radial coupling coefficient α and the material of slotted pipe.

$$\lambda = \lambda\left(W_{\mathrm{J}},\ \alpha,\ f\right) \quad (15)$$

Where, W_{J} is the kerf width, f is a function related to material strength.

Hence, the rising duration of shock wave overpressure of directional fracture blasting with slotted cartridge can be expressed as:

$$T = \lambda \cdot T_{\mathrm{r}} \quad (16)$$

3. Optimization of slotted cartridge blasting device materials

According to the theory analysis in the previous section, there will be no strong compression phenomenon in the direction of pipe thickness in the expansion process of pipe wall under the detonation gas loading, when the rigidity of slotted pipe is bigger (such as steel pipe). Homogeneous expansion occurred in all directions and the change of kerf width is very small when the pipe wall is extruded to the hole wall. With the reducing of rigidity of slotted pipe (such as rigid PVC pipe, thin soft iron pipe etc.) there will be obvious compression phenomenon occurred. At the same time, the lateral deformation of the pipe wall in kerf occurred and the kerf width increased significantly when the detonation gas impact on the pipe wall in kerf. Due to the large amounts of detonation gas gushed from the kerf of pipe, the sparse area will be formed near the kerf in the pipe. The sparse area was supplemented soon by the strong compressed gas and the jet tip of detonation gas should be formed in the inside of the kerf under the wrapped function of pipe wall to the inside detonation gas [7]. In order to confirm the conclusion is correct and choose the optimal materials of slotted pipe, the optimization experiment on the material of the blasting slotted pipe was carried out.

3.1 Experimental program

An open-air experiment using similar rocks should first be carried out on the ground because the working environment in underground is complex and the blasting parameters are difficult to accurately control. According to the results of the open-air experiment and the slotted effect of slotted pipe made by different material, the optimal blasting parameters can be determined. On the basis of the open-air experiment, the typical cross section of roadway must be chosen in the underground experiment. To compare well the effect of slotted cartridge blasting, the contrast experiment is carried out in the underground. The centerline of the roadway should be the center and the slotted pipes on either side adopt different material, but the blasting parameters are exactly the same [6, 17-20]. Finally, the materials and devices of slotted cartridge blasting can be determined and the charge structure can be optimized by the comprehensive analysis of blasting effects of the ground and underground.

3.2 An open-air experiment on the ground

3.2.1 Design of experiment device

A high-rise residential building foundation excavation of Rizhao city of Shandong province was chosen for the test site. Intact granite rock was chosen as the object of the blasting experiment, and the Protodyaknove's number (*f*) of the rock is 7 ~ 9. The diameter of the slotted pipe is 32 mm. Three different kinds of slotted pipe were adopted. The first is made of a thin soft iron which is processed into semicircle. On the spot, two iron semicircular pipes are fixed together with V-shape [6], and the angle is 60 º. In order to achieve the shaped effects, the V-shape could be changed according to the hole location in site [21]. The second is made of stainless steel pipe with 1 mm thick. Along the direction of pipe diameter, kerf width of 2 ~ 3mm is slotted which can be used to achieve the effect of shaped cut blasting [21-22]. The third is made of PVC plastic pipe, and the kerf location and width are the same as the former. Experiments must in the same field conditions. As shown in Fig. 2.

(2a) Thin soft iron. (2b) Stainless steel. (2c) PVC.

Figure 2. The slotted pipe of three kinds of material

3.2.2 The calculation of parameters of blasting experiment

(1) The storage conditions of rock

The blasting digging depth of ground based is 3.0 m. The rock in blasting area is mainly the granite. The thickness of the surface soil layer is 35 cm. The rock is relatively intact and the protodyakonov coefficient is 8~10.

(2) Hole spacing

In order to make it similar to single free surface conditions of roadway, the middle section of intact rock is chosen for the experiment. Considering the reality of mine field, the hole spacing of the test is 450 mm [23], which provide the basis for the next underground test.

(3) Hole charge

According to the dose volume formula, the No.2 rock emulsion explosive is used in the spot and the rock rigidity coefficient is 9. Because this is slotted blasting in intact rock and its goal is mainly to cut rock and observe the effect of the formation seam, the unit explosive consumption should not be taken too large value. According to the parameters of on-site construction and the volume formula [24], the unit explosive consumption can be written as:

$$Q = A \cdot B \cdot W^3 = 1.34 \times 5.07 \times 0.45^3 = 0.619 \text{ kg} \quad (17)$$

Where, A is the resistance coefficient of the rock, A = 1.34; B is the function index of charging, B = 5.07; W is the hole spacing, W = 0.45 m.

Since the weight of each cartridge is 300 g, charge of each hole is 600 g for the convenience of charging.

(4) Plugging length and depth of the hole

The depth of hole should be determined by the minimum plugging length and charge [5]. According to the formula about plugging length of the hole:

$$S = (1.5 \sim 2.2)W = 0.68 \sim 0.99 \text{ cm} \quad (18)$$

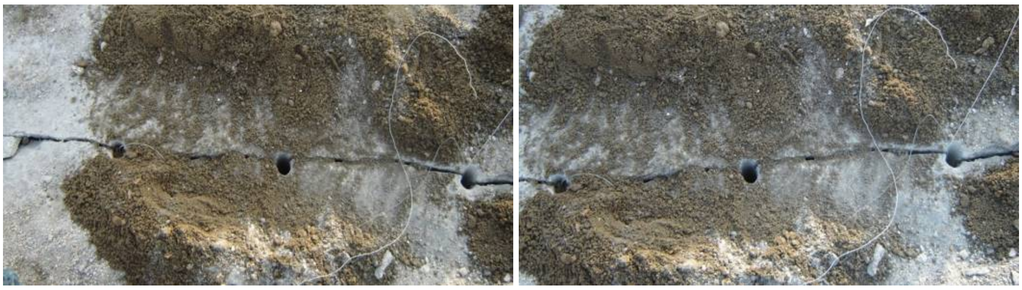
Thus, the minimum plugging length of the hole is 70 cm, then plus two explosives length, finally, the depth of blasting hole is 1.4 m.

(5) The explosives were put into three different slotted pipes. They were detonated by the same section of the electric detonator. The blasting effect is shown in Fig. 3.

One row hole is arranged along straight line for every kinds of slotted pipe and the hole spacing is 45 cm. The No. 2 rock emulsion explosive is used. The charge of each hole is 600 g. the plugging length is 0.7 m. The unit explosive consumption is 1.76 kg/m3. Each slotted pipe hole has adopted instantaneous electric detonator with an initiating explosive [24]. The blasting effect is shown in Fig. 3.

(3a) The thin soft iron slotted pipe

(3b) The stainless steel slotted pipe



(3c) The PVC slotted pipe

Figure 3. The blasting effect of three kind of slotted pipe

The Fig. 3 illustrates that each kind of slotted pipe can slot-through along the hole direction. The rock mass on both sides of hole attachment is basic intact and has no crack. After the excavation, the internal rock mass is relatively intact and has no obvious crack, which was based on the expression of the workers. From the figure of penetrating crack and residual hole after excavation, the slotted seam by PVC pipe is more flat and level and the rock mass along vertical direction is integrity; The heterotrophic micro-cracks come into around the hole of thin soft iron slotted pipe and the secondary interstice are produced within the rock mass; The stainless steel pipe is hard, so it weaken the blasting effect of the rock fracturing; The blasting of one hole is not intact, and the slotting at the bottom of two holes hasn’t breakthrough. So PVC pipe is the best.

3.3 Rock roadway experiment

3.3.1 Engineering instructions

According to the unified arrangement of production management department of Kongzhuang Mine, at least three different roadways should be chosen to carry out the experiment. Then one roadway for the industrial experiment will be determined according to the results. Research group takes into consideration the actual production of coal mine and respectively chose the Eastern belt roadway in the third level, the underground transformer room of a conveyor drive head in IV1 mining area and 7196 return air connection roadway to experiment.

The total length of Eastern belt roadway in the third level is 2470 m. It is mainly in charge of coal transportation of the third level. It belongs to development roadway. Roadway is in the deep level where with high pressure and the roadway is easy to deformed because of compression. The section of underground transformer room of a conveyor drive head in IV1 mining area is relatively large. The lithology of two experiment roadways includes mainly limestone, sandy mudstone, fine sandstone and coal. The total length of 7196 return air connection roadway is about 160 m, which is mainly in charge of returning air of 7196 mining face. It belongs to the preparation roadway. The surrounding rock of the roadway is the roof and floor of No.7 and No.8 coal seam and it is mainly fine sandstone, sandstone and sandy mudstone.

3.3.2 The analysis of first tries effect and selection of experiment roadway

The stainless steel shaped cutting pipe and PVC shaped slotted pipe are selected to make many times experiment in three roadways. The experiment results are shown in Table 1.

Table 1. Analysis and comparison of preliminary tests effects of three roadways

Experiment site	The arrangement of hole	Loaded constitution	Blasting effect description	Existing problem
Eastern belt roadway in the third level	Using the wedge cut. Design cutting hole and reliever hole according to the original procedure. The side holes spacing increased to 400 mm.	Using shaped slotted steel pipe and thin soft iron shaped slotted pipe for side holes. Because of the diameter of hole is small. Three shaped slotted pipe are putted into the hole and the holes are not adjacent.	Half of a hole mark can be seen after hole blasting with slotted pipe. The effect of shaped slotting is not obvious because the hole is not adjacent.	The external diameter of shaped slotted steel pipe is too big and the pipe cannot load in the hole. The thin soft iron pipe is easy to deform and loading speed is slow.
Eastern belt roadway in the third level	Using the wedge cut. Design cutting hole and reliever hole according to the original procedure. The side holes spacing increased to 400 ~500 mm.	The half of side boreholes adopt shaped slotted steel pipe, the other half is PVC pipe. In addition to the individual holes failed to load, the most was putted into the slotted pipe according to the requirements of design.	After blasting, the effect of PVC pipe is better than steel pipe. The ratio of half-hole marks of the shaped pipe can reach 80%. The average utilization ratio of hole is 90.	There have cap wires at the end of shaped slotted pipe. When the stemmer was put into cutting pipe, it is easy to poke broken cap wires. In this case, it can cause misfire, especially steel pipe.
Underground transformer room of a conveyor drive head in IV1 mining area	Using arch section and wedge cut. There are strict requirements of smooth blasting for hole design. The side holes spacing is 500 mm.	The side holes use PVC shaped slotted steel pipe. The end of slotted pipe tightly with a cork, and the open end to entangle with tape. Slotted seams are arranged in strict accordance with the contour line of roadway, stemming the end by clay.	After blasting, the effect of smooth blasting is very good. The ratio of half-hole marks can reach 100%. The utilization ratio of hole is closes to 100%.	Due to the workers don't understand the mechanism of shaped slotted blasting. The charging time is long and the operation process is more complicated.

7196 return air connection roadway	Using the wedge cut. Design cutting hole and reliever hole according to the original procedure. The side boreholes spacing increased to 450 mm.	The side holes use PVC shaped slotted steel pipe. The end of cutting pipe tightly with a cork, and the open end to entangle with tape. Slotted seams are arranged in strict accordance with the contour line of roadway, stemming the end by clay.	After blasting, the effect of smooth blasting is very good. The ratio of half-hole marks can reach 90%. The utilization ratio of hole is closes to 100%.	The excepted goals and requirements are basically achieved.

Through the comprehensive comparison and analysis of the above factors which includes the effect of four blasting experiment, the difficulty of slotted pipe processing, roadway geological condition and the convenience of charging operation, the 7196 return air connection roadway was chosen as the experiment roadway for the small-scale industrial experiment. From the penetrating cracks in Fig. 3, the effect of PVC slotted pipe is better and the rest of the two kinds of slotted pipe are poor. The internal rock mass has the secondary cranny. Considering comprehensively the blasting effect, economic practicality, difficulty of operation in the processing of production and construction of the three slotted pipes, the PVC pipe was determined to use.

4. The design and application of shaped cut blasting device

4.1 The shaped cut blasting device and the design of blasting parameters

The distance of side boreholes was expanded to 450 mm in the process of the experiment by calculation and analysis. Because the maximum of construction condition limits should not exceed 500 mm. The explosive adopt T320 which is safety explosive. The charge of each hole is 600~900 g. The lower limit of plugging length is 0.6 m [24]. In charging process, explosive with PVC shaped slotted pipe is only put in side boreholes. The pipe seam of slotted cartridge (decoupling charge) is in accordance with the contour direction of roadway layout [10-13]. It will lead to the worse effect if the difference of the direction placement of pipe seam is too big, even on the contrary. When the cutting cartridges were placed, the orifice end was plugged with a cork [17, 25]. When the explosive was put into by using a stemmer, the detonator wire should be grabbed gently. Anyone should not turn the stemmer when the cartridge is put into bottom of the hole. The direction of cartridge kerf should be consistent with the contour of roadway. When the cutting cartridge is in its place, there need to plug into small pieces of stemming. The shaped cut blasting pipe and charge structure of side boreholes were shown in Fig. 4. The diameter of PVC pipe is 32 mm and the thick is 1 mm; the width of cutting seem is 2~3 mm [22]. To compare the smooth blasting effect of shaped cutting pipe, the other holes were charged by the operation procedures of design. The arrangement of experiment hole was shown in Fig. 5.

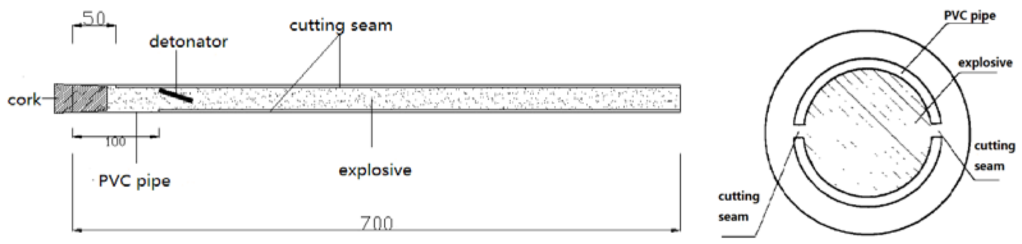


Figure 4. Charge structure diagram of shaped cut blasting pipe of side boreholes

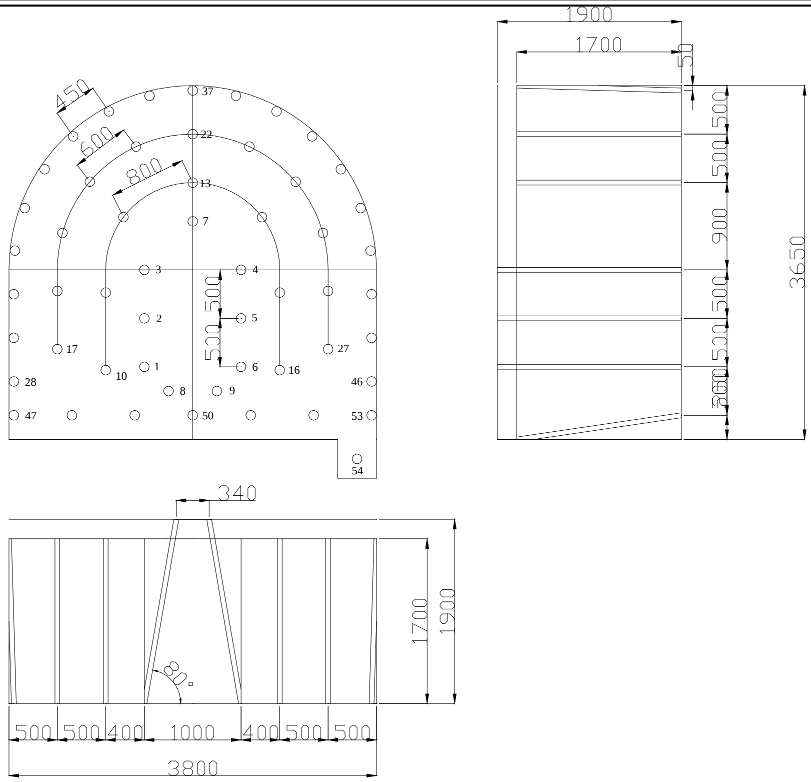


Figure 5. The arrangement diagram of whole-section hole, adopted by the experiment

4.2 The analysis of experiment results

The layered driving was adopted in the site. The blasting effect when shaped slotted pipe was working in the higher slice was only analyzed.

4.2.1 Hole utilization

Hole utilization is the key indicators of blasting effect and directly determines the driving single penetration, and it can affect the economic benefits. Through the comparison and analysis of the experiment, the directional fracture blasting with slotted cartridge of side holes can't affect the utilization ratio after blasting. Otherwise, this will deviate from our initial idea. The comparison between the data of hole utilization during and before the experiment were taken (Fig. 6). The horizontal axis in the graph said the experiment number of the collection data, the vertical axis said the hole utilization.

The Fig. 6 illustrates that the PVC shaped cutting pipe which was used in side boreholes does not reduce the utilization ratio of hole, on the contrary, it improves the utilization ratio in most of experiment. Utilization ratio of holes also depends on the arrangement and charge structure of cutting hole and reliever hole. Therefore, if the goal of expected blasting effect of PVC shaped cutting pipe could be meet, all aspects of the influence factors need to consider and further research.

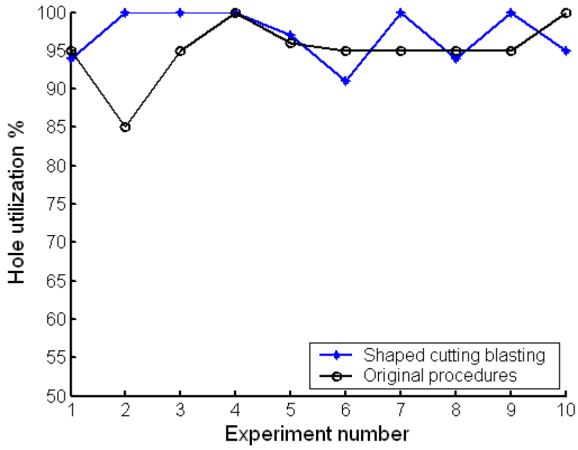


Figure 6. The contrast figure of hole utilization before and after experiment.

4.2.2 Other blasting effect parameter comparison before and after the experiment

For a more comprehensive research on the advantage and disadvantage of the PVC slotted pipe in the roadway drivage blasting, some more data were counted in the process of experiment, which can reflect the blasting effect. It was under the condition that does not change the original procedures design parameter and charge structure of cutting hole and reliever hole. The related data was compared. They include dosage of detonator of side hole, explosive dosage, side hole spacing, diameter, nicked rate of side borehole, the degree of over-break, drilling time of side hole, the average charging time of side hole, the utilization ratio of hole etc. [12]. The contrast table of effect parameters of before and after experiment was shown in Tab. 2.

Table 2. The contrast table of blasting effect of higher slice on single cycle before and after the experiment

Comparative item	Original operating practices	Shaped experiment
Explosive factor(kg/m^3)	1.0~1.51	0.7~1.22
Explosive consumption of average per meter (kg/m)	28.8	16.28
Detonator consumption of average per meter (number/m)	36.5	31.7
Explosive consumption of per tour (kg)	30.94	24.84
Detonator consumption of per tour (number)	62	54
Overall length of hole of per tour(m)	106.6	91.3
Advance of working cycle(m)	1.6	1.7
Detonator dosage of side borehole(number)	17	13
Explosive dosage of side borehole(kg)	12.8	9.2
Space of side borehole(mm)	300	450
Diameter of side borehole(mm)	36	42
Nicked rate of side borehole (%)	≤50%	85~100%
Average of the nicked rate of side borehole (%)	≤50%	92.7%
Degree of over-break tunnel wall(mm)	100~400	30~120
Drilling time of side borehole (min)	50	45
Average loading time of side borehole (min)	20	20

4.2.3 Results and discussion

Based on the field experiment in 7196 return air connection for nearly half a month, the following achievements have been made:

(1) The laneway periphery molding is more regular than before. The size of laneway periphery outline meets the design requirements. The rock wall is relatively flat. The size of under-break and over-break is not more than 3cm and 12cm, respectively. The fluctuation difference of rock can be controlled in 10 to 15 cm. The roughness and hole trace save rate of side borehole is required more strictly than ordinary smooth blasting, which provides a more favorable conditions of late support. The support quality was greatly improved and the support time was greatly reduced.

(2) The spacing of side hole is increased appropriately and reaches 450 mm by means of directional fracture blasting with slotted cartridge. There is no obvious advantage in reducing drilling time because of using the 42 mm drill bit due to the limits of slotted pipe in the experiment. But the time in processing dangerous stone and under-break or over-break stone was significantly reduced and the overall time was shortened.

(3) After blasting, the rate of half-hole mark of side hole on rock wall is: The solid and holistic rock is greater than or equal to 95%; The medium hard rock is not less than 85%; The soft rock or the rock with jointing growth is greater than 75%. There wasn’t crushing and obvious cracks on the hole wall (refer to the new fracture of blasting, except native bedding joints) after the blasting. It has a mild damage to surrounding rock or rock mass. It can improve the stability of surrounding rock and reduce the dosage of supporting materials (such as shotcrete, mesh) and reduce the costs of support.

(4) There were not big dangerous rocks and pumices in the roadway where the geological structure is soft and broken, and there were no dangerous stone or seldom in the part where the geological condition is good after blasting.

(5) The “steps” at the connecting of two rows should be controlled within 10 to 12 cm.

5. Conclusions

Results of the experiment of slotted pipe with different materials indicate that the strength of the pipe had a great effect on stress field distribution in the blast hole. The convergence effect of pipe wall to the explosion energy reduced when the strength of pipe reduced. The explosion energy basically all wrapped inside the pipe wall when the pipe wall is made from rigid materials and there will be a very little convergence effect when soft iron.

Based on the slotted cartridge blasting experiment on the ground and in the underground, the blasting device and charge structure with PVC slotted pipe which was closed at one end was proved to the optimal blasting scheme. The shaped blasting devices can improve the effect of smooth blasting molding in rapid advance of roadway. The roadway or outline of tunneling can get a good molding effect and the smoothness is high. The hole trace save ratio can reach more than 90% in directional fracture blasting of side borehole of whole-section. Through the directional fracture blasting with slotted cartridge, the hole spacing was expanded from 300 mm to 450 mm, which increases more than 50%. The charge decreased 20.5%, when it was compared to the original plan. This blasting device reduced the explosive factor and rate of drilling hole. The cost was also decreased. Good molding of roadway can reduce the consumption of shotcrete-bolt material and work hours. The stability of surrounding rock can be improved. The damage of surrounding rock is effectively reduced in the blasting. The rapid advance of roadway with high production and efficiency is conducive to be achieved. But the blasting device of slotted pipe and coupling mechanism of holes need to be further researched.

Acknowledgements

This work was supported by Shan-dong Provincial Natural Science Foundation (ZR2013EEM023), the Open Project of State Key Laboratory Breeding Base for Mining Disaster Prevention and Control (Shandong University of Science and Technology) (NO. MDPC2012KF12), Taishan Scholarship Project of Shandong Province, China (No. tshw20130956), the Project of Shandong Province Higher Educational Science and Technology Program (J14LG06), the Project of Qingdao Construction Technology Program (JK2012-24), the Project of Shandong University of Science and Technology Graduate Innovation Fund(YC140323).

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