Analysis on Blasting Effect of Parallel Cut with Empty Hole in Tunnel Construction

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Abstract. Establishing a calculation model for parallel cut blasting effect has certain practical significance for guiding tunnel blasting construction. A calculation model of cutting blasting effect is established based on the theoretical analysis in this paper. Under certain conditions, the quantitative relationship between the cutting efficiency and the hole diameter, the depth of the cut hole and the hole distance between the cut hole and the empty hole is obtained. The calculation results of the model are consistent with the results of a pure cutting test, which shows that the calculation model is reasonable.

Keywords. Blasting excavation, parallel cut, blasting effect, field test.

1. Introduction
Cut blasting is a key technology in tunnel driving [1]. The spread patterns of cut holes are various based on different tunnel sectional fractures, rock nature and geological structures, etc. [2-4]. In general, parallel cut and angled cut are the two major patterns. Seeing from the extent of blasting difficulties, parallel cut is more complicated and strict. But the using frequency of parallel cut with blasting hole is higher. The depth of blasting hole would not be confined by tunnel section fracture [5, 6]. In order to speed up tunneling and increase single footage, parallel cut must be adopted. Therefore, parallel cut is a development trend.

The mechanism of parallel cut is complicated and mainly can be seen in the following aspects [7-10]: parallel cut involves the whole process including blasting effect, stress field distribution, rock crushing and tossing; The cut blasting effect is a three dimensional problem which is obviously more complicated than one or two dimensional problem. Cut blasting is a near field blasting. The mechanics behavior of the blasted medium under the blast loading effect is featured by nonlinearity. Cut blasting is a combined effect of a group of blast holes but not a matter of axial symmetry. The calculation is more challenging due to the wider range it requires. Based on the above reasons, the mechanism research of cut blasting is not deep enough as compared with perimeter blasting, step blasting, tossing blasting and tearing down blasting. Therefore, to set up the parallel cut blasting effect calculation model and to guide the tunnel blasting construction is of realistic significance.

2. The Establishment of the Blasting Effect Analysis Model of Parallel Cut with Empty Hole
The purpose of cut is to excavate a hole in flat land which creates a positive new free section for the follow up blast hole initiation. Therefore, cut blasting is a form of strong blasting which can easily be stuck by rocks. In driving blasting (especially in deep hole blasting), whether if the cut succeed will pretty
much depend on the cut blasting efficiency which is the formed area and depth of cut cavity. In a word, the efficiency of tunnel excavation blasting can be concluded to the status of rock fragments discharge in cut cavity when cut blasts.

Research shows there are two stages for the tossing of parallel cut blasting with empty hole: Firstly, the blasting of explosive powder filling hole crushes the medium and moves to the direction of the empty hole. Next, due to the blasting gas expansion, the crushed medium starts to be tossed along the free section of cut cavity opening. The movement of fragments in discharge process is like one dimension. In order to make it easier to analyze the process of fragments discharge in theory, the spiral cut effect analysis model only considers the blasting model for the initial blasting of explosive powder filling hole. The basic hypothesis has been made as follows: The pressure of blasting gas inside cut cavity is even at every moment. The blasting stress waves crush the rocks in cut cavity. However, the effect to the tossing speed is minor enough to be neglected. After the rocks crushed, blasting gas immediately flow to the crushed rocks, expands and tosses rock fragments. The cut blasting hole is sealed well. The wall of cut cavity is smooth. The time length of the initiation of the cut hole 2# lasts long enough.

2.1. Physics Model for the Fragments Discharge Process of Parallel Cut Blasting

After explosive powder filling hole of spiral cut initially blasted, the rocks between filling hole and empty hole are crushed and firstly move to the direction toward the empty hole and be bounced back by knocking onto the correspondent empty hole walls and blasting gas and rock fragments immediately mix together. In view of simplifying calculation and based on the basic hypothesis, we further suppose the penetration of the blasting gas only happen in the range of explosive powder filling part. Therefore, the discharge of rock fragments inside cut cavity can be calculated respectively in the following two areas: I. Blasting gas penetration area; II. Blasting gas none penetration area (See figure 1).

2.1.1. Blasting Gas Penetration Area (Area I). Area I contains high pressure gas and fragments (the loose part). According to the crushing nature, the rocks inside slot cavity were smashed. Based on the documents, the mixture of the blasting gas and the rock fragments in area I can be seen as a two-stage flow. But the horizontal size of cut cavity is far shorter than the vertical one; the two-stage flow problem can be treated as one dimensional problem.

With the expansion of the high pressure gas in area I, the rock fragments were also driven to move and toss outward.

2.1.2. Blasting Gas None Penetration Area (Area II). In the none penetration area, there are only rocks. They are sheared under the pressure between expansion and cut cavity wall in Area I. In view that the rocks only move to one direction and the deformation under the expansion pressure is minor or even can
be neglected (taking rocks as rigid parts). Out tossing rocks of area II is the extension of the two-stage flow movement in area I.

2.1.3. Different Blasting Fragments Discharge Process between Deep Hole and Shallow Hole Parallel Cut. In parallel cut blasting, the ratio $\varepsilon$ between the explosive powder filling length $l_e$ and the part without explosive powder $l_o$ vary from condition to condition (See table 1).

| Blasting Condition            | $\varepsilon = l_o/l_e$ |
|------------------------------|----------------------|
| Shallow Hole Blasting (<1.8m) | <1.7                 |
| Medium Deep Hole (1.8–2.5m)  | 1.7–2.0              |
| Deep Hole (2.5–5m) Blasting  | 2.0–2.5              |
| Super Deep Hole (>5m) Well   | >2.5                 |

Different $\varepsilon$ value, different fragments discharge process. When $\varepsilon >2$, when the explosive powder filling part is pretty long, especially the hole is deep enough to be a well, fragments discharge movement will mainly happen in the blasting gas penetration area (area I). Area II is shorter than area I, it has less impact on area I as well. The treatment of rocks movement in area II can be further simplified. When $\varepsilon <2$, due to shorter explosive powder, especially the shallow hole blasting, the rocks movement in area II has greater impact on the fragments discharge in area I. So under these circumstances, the rocks movement in area II can not be simplified.

2.2. The Fragments Discharge Process of Parallel Cut Blasting

Due to that the movement of Area II is the extension of two-phase flow movement of area I, so the movement regulation of area II should enjoy the priority to be considered firstly.

2.2.1. Area II. Suppose $x(t)$ is the interface of area I and II, on the interface, being pressed by the expanding blasting gas in area I. Meanwhile, rocks in area II suffered from the shear stress of cut cavity. According to Newton's Second Law, the rocks movement regulation of area II is:

$$P \cdot S - L \varepsilon \cdot \tau = S l_e \rho_m x''(t)$$  \hspace{1cm} (1)

In the equation: $P$ is mixture pressure of rocks and blasting gas; $S$ is cross section area of the cut cavity; $L$ is cross section perimeter of the cut cavity; $L_e$ is length of the part without explosive powder; $\tau$ is shearing strength; $\rho_m$ is average density of the rocks in area II. $S$ is according to blasting gas status equation.

$$P = P_0 \left( \rho / \rho_0 \right)^r$$  \hspace{1cm} (2)

In this equation; $P_0$ is initial pressure; $r$ is blasting gas polytrophic index $r = 1.4$, and

$$\rho / \rho_0 = \left( L_0 + x(t) \right)$$  \hspace{1cm} (3)

Coupled with above equations we get:
\[
P_0 \left( L_0 / \left( L_0 + x(t) \right) \right)^{1.4} S - L_L L_x \tau = SL_x \rho_w x^4(t) \tag{4}
\]

The initial condition of the equations: \( t = 0, \ x(0) = x'(0) = 0 \)

Integrate equation (4), the rocks movement regulation of area II is;

\[
5P_0 SL_0 \left[ 1 - L_0^\alpha / \left( L_0 + x(t) \right)^{\nu_0} \right] - 2LL_x x(t) = SL_x \rho_w \left[ x'(t) \right]^2 \tag{5}
\]

When \( x(t) = l_v \), we get the rock tossing speed in area II.

2.2.2. Area I. When rocks of area II totally come off the cut cavity and start to toss out at the speed of \( x'(t) \), the mixture gas in area I constantly expand and drive the crushed rocks move vertically inside the slot cavity. According to the documents, below is an equation of the two-phase flow of area I, the movement speed at every position and at a certain moment with the initial speed at the correspondent position.

\[
v^2_x = v^2_x + 2Kx^\gamma \left[ \left( x + \xi \right)^{\gamma - 1} x^{\gamma - 1} \right] / (\gamma - 1) \tag{6}
\]

In the equation: \( v_x \) is the flowing speed at the starting moment \( x \) for the two-phase flow which consists of blasting gas and rock fragments; \( v_x \) is the two-phase flow distance at \( x \) is the speed after \( \xi \); \( \gamma \) is blasting gas polytrophic index.

\[
K = P_0 l/v \cdot S \rho_0 \tag{7}
\]

In the equation: \( P_0 \) is initial pressure of blasting gas; \( f \) is rocks fraction coefficient; \( c \) is cross sectional perimeter of cavity; \( S \) is cross sectional area of cut cavity; \( \rho_0 \) is rock fragments quality of the unit volume for the two-phase flow at the beginning.

From the beginning of the movement of two-phase flow in cut cavity to the end, movement positions of different points along the cut cavity on the vertical direction are different. Suppose when the movement stops \( v_x = 0 \) and \( x + \xi = L \). When the two-phase flow movement stops, \( x \) point will be right on the top of the cut cavity. The rock fragments behind \( x \) will remain inside the cut cavity, so we get:

\[
0 = v^2_x + 2Kx^\gamma \left[ L^{\gamma - 1} - x^{\gamma - 1} \right] / \gamma - 1 \tag{8}
\]

In this equation, \( v_x \) can be getting as \( v_x = x'(t) x / L \) according to the initial tossing speed of area II. So from the above equation, we can get the position of the tossed and the remained rock fragments so as to get the volume of the remained rock fragments inside the cut cavity when the cutting blast was over; suppose \( z \) is the residual rate of rock fragments inside the cut cavity when blasting was over, then:

\[
z = V_x / V_0 \tag{9}
\]

In this equation: \( V_x \) is the remaining rock fragments volume in cut cavity when blasting was over; \( V_0 \) is cut cavity volume; \( z \) reflected the amount of the remaining rock fragments in cut cavity when the cutting was over. The smaller \( z \) is, the better effect the cutting effect is.
3. The Calculation of the Cut Cavity Tossing Effect

When the cutting blast is over, the remained rock fragments inside the cut cavity is the key indicator which reflects the quality of cutting because the purpose of cutting is to provide maximum compensating space for the crushing of the follow-up blasting holes; when the cutting blast is over, the smaller the rock fragments volume is, the more obvious the cutting effect is. So \( z \) can be used to balance the tossing effect of the cut blasting. In value calculation, the parameters should be chosen from the following table:

| Slot aperture \( R_1 \) (m) | Initial pressure of blasting gas \( P_0 \) (MPa) | Rock shearing strengths \( \tau \) (MPa) | Rock density \( \rho \) (Kg/m\(^3\)) |
|---------------------------|------------------|----------------|----------------|
| 0.04                      | 200              | 8.50           | 2700           |

3.1. The Connection between \( z \) and \( L \)

In the calculation, we get empty hole semi diameter \( R_2 = 0.08 \) m, the cavity hole and empty hole space are respectively 0.15, 0.20, 0.25. We get three curves based on the connections between \( z \) and \( L \) under three different conditions. From the figure 2, as the hole is getting deeper, the residual rock fragments inside cut cavity are getting less. It can create favorable conditions for the following up hole blasting and guarantee the maximum hole depth and footage.

3.2. The Connection between \( z \) and Empty Hole Aperture \( R_2 \)

When calculating, the distance between empty hole and cavity hole \( a = 0.20 \) m. Seeing from the result of figure 3, the fact can be seen that the bigger the empty hole aperture is, the smaller the rock fragments are in cut cavity when blasting. This can be mainly explained by the following two reasons: The increased empty hole aperture makes the volume ratio of rock fragments before and after blasting become less. The increased empty hole aperture created a favorable condition for cut blasting and change its blasting effect. So under the accepted condition, the empty hole aperture can be increased as much as possible. It can not only improve blasting effect but also expand cutting range.

Figure 2. The connection between \( z \) and hole depth \( L \).
3.3. The Connection between $z$ and Hole Spacing $a$

In calculation, the empty hole aperture $R_2=0.08$. Seeing from the curve in figure 4, enlarging the space of cut hole and empty hole will make the residual rock fragments inside cut cavity increase which also means that $a$ can not be enlarged unlimitedly. The cutting area will be confined. Appropriate a value will guarantee the blasting effect as well as certain area for cut.

4. Engineering Practical Case

In view of checking the reliability of above calculation model, now we apply the said blasting effect analysis into a pure cutting blast test of Jinchuan Second Mine located in Kuangjin Road, Zhang Zimian. Big empty hole spiral cutting was adopted in the test. The diameter of empty hole and 1# cut hole are respectively $\Phi 85$ mm and $\Phi 40$ mm, the hole depth are 3.6 m and 3.4 m; the space between cut hole and empty hole is 200 mm. Adopting reverse initiation with coupling explosive powder filling, blocking length is 50 mm; rock density on the spot is 2.45 g/cm$^3$, shearing resistance is 8.0 MPa. See below calculation process:

4.1. Cut Cavity Parameter

\[ c = 2 \left( R_1 \left( \frac{\pi}{2} - \theta \right) + R_2 \left( \frac{\pi}{2} + \theta \right) + a \cos \theta \right) = 0.5989m; \text{ Within which } \theta = \sin^{-1} \left( \frac{R_2 - R_1}{a} \right); \]
\[ S = \frac{1}{2} \left[ (\pi - 2\theta)R_1^2 + (\pi + 2\theta)R_2^2 \right] + a(R_1 + R_2)\cos\theta = 0.016m^2; \quad \text{volume} \; V = SL = 0.0544m^3; \quad (11) \]

### 4.2. The Blasting Parameter of Explosive Powder in Blasting Hole
Blasting pressure \( P_0 = 0.25\rho D^2 = 3240 \text{ MPa} \); the area the blasting gas occupies in area I
\[ V'_0 = \pi \left( R_1^2 + R_2^2 \right) L_Q = 0.020m^3 \quad (12) \]

The volume of the part with explosive powder filling hole \( V_0 = \pi R_1^2 L_Q = 0.0038m^3 \); The initial pressure of blasting gas
\[ P_0 = P \left( \frac{1 - 0.556}{V'_0/V_0 - 0.556} \right)^\frac{4}{7} = 139\text{ MPa} \quad (13) \]

### 4.3. Rock Initial Tossing Speed in Area II
Calculate the initial speed into the following equation:
\[ 5P_0 S L_Q \left[ 1 - \frac{L_0^4}{(L_0 + x(t))^4} \right] - 2cL \alpha(t) = SL_0 \rho_m [x'(t)]^2 \]
\[ x'(t) = 124m/s; \quad (14) \]

### 4.4. Calculate the Residual Ratio of Rock Fragments in Area I
Calculate the initial speed into the following equation:
\[ 0 = \frac{x'(t)x}{L} + \frac{2Kx'}{\gamma - 1} \left[ L^{1-\gamma} - x^{1-\gamma} \right] \]
\[ x = 3.39 \text{ m}; \quad \text{So, the residual ratio of rock fragments inside cut cavity is:} \]
\[ z = \frac{xL_Q}{L^2} \times 100\% = 85.06\% \quad (15) \]

In the filed testing, most of the rocks in the cut cavity were crushed but not yet been tossed out. The hole depth after blasting is the visible blasting funnel which is approximately 0.5 m.

The rock fragments residual ratio:
\[ Z = \frac{3.4 - 0.5}{3.4} \times 100\% = 85.29\% \quad (17) \]

Seeing from the equation, the field testing result is in line with the calculation result of the model.

### 5. Conclusion
The thesis set up the calculation model upon cut cavity blasting effect and reached the result. Under the certain circumstances, the big hole aperture, the cut hole depth, the space between cut hole and empty hole are respectively related to quantities cut cavity efficiency. The calculation result from the calculation model is in line with the field cut cavity testing result. It also indicates that the calculation model is appropriate.
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