Vibration Reduction Mechanism and Experiment of Stepped V-Cut Millisecond Blasting

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ABSTRACT

As drilling and blasting are carried out in an urban tunnel, which is adjacent to existing buildings or structures, the balance between blasting-induced vibration reduction and drivage efficiency is a very important problem that must be resolved properly. Therefore, a new cut blast method named Stepped V-cut millisecond blasting (SV-cut) was developed by optimizing the most common used Vertical V-cut blasting method (V-cut). The most significant features of SV-cut lie in the utilization of sub-level interval charging structure and millisecond delay blasting technology in the cut hole and the cut cavity formed from outside to inside sequentially. SV-cut provides advantages of high borehole utilization ratio, low vibration level and satisfying advance per round. Based on the principle of millisecond blasting, the rock fragmentation process and the vibration reduction mechanism of SV-cut are analyzed. Methods of determining blasting parameters, which have significant effects on vibration intensity and cut cavity formed quality, are proposed according to the forming requirements of both outer and inner cut cavity and vibration reduction. In order to compare the cut blast effect and vibration intensity between SV-cut and V-cut, field blasting experiments were performed in the blasting engineering of the Yamalike twin-arc tunnel, which closely passes over existing parallel tunnels. Blasting results show that SV-cut blasting has proven to be an effective tunnel blasting method for both increasing blasting effects and decreasing blasting vibration. Comparing SV-cut with V-cut, SV-cut can increase blasting drivage by about 8.5% and reduce vibration intensity induced by cut hole blasting by at least 30%.

KEYWORDS: Drilling and blasting, Stepped V-cut, Blasting vibration reduction, Field blasting experiments.

INTRODUCTION

With the significant urban infrastructure development and upgrading in China, many tunneling blasting projects adjacent to existing surface buildings or underground structures have appeared. Damage control of buildings and structures, caused by vibration from drilling and blasting utilized in tunnel construction, is a significant issue that must be settled (Kolymbas Dimitrios, 2005; Jiang et al., 2011). Presently, a variety of methods have been proposed to
reduce and control blasting-induced vibration to a permissible level, such as multi-millisecond blasting with short advance per attack, presplit blasting, drilling absorption holes and taking duplex cut method (Walsum, 1991; Zhang et al., 2005; Yang et al., 2013). These methods can effectively reduce blasting-induced vibration to some extent, but these methods lead to poor drivage efficiency and expensive construction cost due to the increased number of boreholes or the decreased advance per round. To surmount these deficiencies, air-space charging structures and waveform interface are put forward, which have proven to be effective in theory (Yang and Zhang, 2010; Wang et al., 2013). However, these two methods rarely achieve satisfactory reduction effects in the field, due to the complex charging process, quality of detonator, complex geology condition, as well as due to other factors. Therefore, it is particularly urgent to develop a feasible, simple and convenient vibration reduction blasting method for tunnel construction, which not only reduces vibration, but also improves construction efficiency.

In fact, clearing the characteristic of blasting-induced vibration enables researchers to develop an advisable and feasible blasting method for reducing vibration. Some scholars have demonstrated that vibration intensity is totally different with different types of borehole blasting. Generally, the vibration intensity of cut blasting is most intensive, because of the strong blasting clamping force and highly explosive charging degree of cutholes (Berta, 1994; Zhang et al., 2005). So, optimizing the cut method is the most pivotal problem to develop an advisable and feasible vibration reduction blasting method. Nowadays, there are many cut methods utilized in tunneling blasting. V-cut has been welcomed by most of the users, because its drilling technology is simple with fewer holes and it is easy to get a perfect cut cavity. Taking the aforementioned advantages of V-cut into account, a newly cut blasting method named stepped V-cut millisecond blasting is developed, which stems from the common used vertical V-cut millisecond blasting.

Based on the principle of millisecond blasting, SV-cut blasting process and its vibration reduction mechanism are analyzed and the methods of determining the key blasting parameters are put forward. Field blasting experiments of both SV-cut and V-cut are carried out in the Yamalike twin-arc tunnel in Urumqi, China. According to analyzing and comparing blast results, this paper studies both drivage efficiency and vibration reduction effect of SV-cut.

**Patterns and Charging Structure of SV-cut**

On the basis of the commonly used V-cut blasting method, the SV-cut millisecond blasting method is proposed by optimizing cuthole patterns, dividing explosives into two decks with different igniting delay times. Charging structure and ignition sequence of V-cut and SV-cut are shown in Figure 1. It can be seen that the cutholes’ layout of both SV-cut and V-cut adopts almost the same pattern. The main differences between the two methods are that the explosives are decked and that different igniting times from outside to inside are adopted.

The cut blasting process of SV-cut includes the following two steps. Step1: as shown in Figure 1(b), the outer deck is ignited first. Then, under the blasting load caused by the explosive of the outer deck, fractures around each cuthole are formed and interlaced together and rock of the outer cavity will be fragmented along the axis of each cuthole pair. At the same time, the expansion pressure of gases leads to rock fragmentation heaves, creating a trapezoid-shaped outer cavity (see Figure 2). The newly created cavity bottom face has many blasting-induced fractures and will be the free face for inner-deck blasting. Step2: with the ignition of the inner deck dozens of milliseconds later, blasting load caused by inner deck explosive will force the rock to be crushed and fragmented into pieces, especially by the new created free face, after rock pieces are ejected out of the V-shape cavity finally created (see Figure 2).
Cutting Process and Vibration Reduction Mechanism of SV-cut

In V-cut, the charging length is \( l_0 \) and the line of least resistance is \( w_0 \) (see Figure 1(a)). In order to create the entire cut cavity by one-step, all of the charged explosives in the cutholes must be ignited at one time. During this cut blasting process, a very large clamping force of rock has to be surmounted, which leads a great deal of explosive energy to enter the reserved rock and produce a strong environment vibration.

But in SV-cut, the forming process of the entire cut cavity divides into two steps due to the utilization of interval charging structure and millisecond blasting method in cutholes. Charging lengths of the outer deck and inner deck are \( l_1 \) and \( l_2 \), respectively, being much smaller than in V-cut. Correspondingly, the weight of explosive needed to be ignited in each step drops by \( l_1/l_0 \) and \( l_2/l_0 \) of that in V-cut, respectively. At the same time, the lines of the least resistance of inner deck and outer deck also reduce by \( w_1/w_0 \) and \( w_2/w_0 \) of those in V-cut, respectively. This means that the clamping force of rock decreases significantly, less explosive energy goes into the reserved rock and the environment vibration will be reduced.

Key Blasting Parameters in SV-cut

Angel of Cuthole

The angle of cuthole may be determined according to the clamping force and rock fragmentation degrees of the outer and inner cut cavity. Usually, to ensure the rock being fragmented and thrown out thoroughly, the arrangement of the cuthole should meet the following requirements: the bottom of outer and inner charged explosive columns should be arranged in the fissured zone and the crushed zone, respectively, following two formulae that should be simultaneously met.

\[
D_i > 2R_f, \tag{1}
\]
\[ D_2 > 2^2 R_c, \]  
\[ R_f = \text{fracture area radius around the center of borehole.} \]
\[ R_c = \text{cracked area radius around the center of borehole.} \]
\[ a = \text{impact factor of stress superposition, which generally equals 2.1~2.3 (Dai Jun and Du Xiaoli, 2011).} \]

Combining with the geometric relationship of per cut hole pair as shown in Figure 1, the angle of cut hole can be calculated by using Eq. 3.

\[ \theta = \arctan\left(\frac{L_1 + L_2}{D_1 - D_2}\right), \]
\[ \theta = \text{angle of cut hole (rad).} \]
\[ L_1 = \text{depth of outer deck bottom.} \]
\[ L_2 = \text{depth of inner deck bottom.} \]

**Charging Parameters**

The most important charging parameters include charging depth ratio and charging weight ratio between outer deck and inner deck.

Charging depth ratio between outer deck and inner deck is defined as:

\[ K_L = \frac{L_1}{L_2}, \]
\[ K_L = \text{charging depth ratio.} \]

where, \( K_L \) is of great connection with the blasting clamping force of each step and the effect of cut blasting and vibration reduction. Generally, \( K_L \) equals 1.5~1.8 (Zong, 1992).

Due to both clamping force of each step and the shaping requirement of outer and inner cut cavity being different, the charging weights of outer deck and inner deck vary. This paper defines charging weight ratio between outer deck and inner deck as:

\[ K_Q = \frac{Q_1}{Q_2}, \]
\[ K_Q = \text{charging weight ratio.} \]

where, \( Q_1 \) = charging weight of outer deck.
\( Q_2 \) = charging weight of inner deck.

Here, \( Q_i \) (i=1, 2) can be calculated according to the following equation:

\[ Q_i = q_i V_i / N, \]
\[ \text{where,} \]
\[ q_i = \text{unit explosive consumption;} \]
\( q_1 / q_2 \) equals 0.3~0.5 kg/m³ (0.5~0.8 lb/yd³).
\( V_i = \text{volume of cut cavity.} \)
\( N = \text{number of cut holes.} \)

**Millisecond Delay Time**

Generally, an advisable millisecond delay time can both improve cut blasting performance and decrease vibration intensity.

Blasting process of outer cavity includes three stages: explosive detonation, rock fragmentation and swelling, as well as rock piece throwing. The millisecond delay time should meet the following equations simultaneously (Feng, 1980; Zhen and Zhu, 2005).

\[ \Delta t > t_1 = \frac{L_o}{C_e} + L_o \sin \theta / V_f \cos (\beta/2) + k_p S / V_p \quad (7) \]
\[ \Delta t > t_2 = k_l \ln R_c, \quad (8) \]

where,
\( \Delta t = \text{millisecond delay time.} \)
\( t_1 = \text{duration of outer cavity blasting.} \)
\( t_2 = \text{action duration of positive phase stress wave.} \)
\( L_o = \text{charge length of outer deck.} \)
\( C_e = \text{detonation velocity of explosive.} \)
\( V_f = \text{crack propagation speed; here,} \) \( V_f = 0.38 C_p \) and \( C_p \) is the elastic wave velocity of rock.
\( \beta = \text{angle of blasting crater.} \)
\( S = \text{distance between broken rock and newly created free face; here,} \) \( S = 0.01~0.02m \) (0.39~0.78 in).
\( V_p = \text{throwing speed of broken rock fragments; here,} \) \( V_p \) equals 4~7m/s (13~23 ft/s).
\( k_p = \text{clamping factor of rock; here,} \) \( k_p \) equals 2~4m/s (7~13 ft/s).
Field Experiment

Site Description

Blasting experiments were performed in the right main tunnel of Yamalike twin-arc tunnel, Urumchi, China. Yamalike twin-arc tunnel is a shallow buried (the maximum burial depth is 30m (98 ft)) asymmetrical tunnel, which is needed to entirely cross closely over existing parallel tunnels and parallel with a railway tunnel, as shown in Figure 3. The space between main tunnel and existing parallel tunnels is 1.8~5m (5.9~16.4 ft) in transversal direction and 10.8~12.1m (35.4~39.7 ft) in vertical direction.

![Twin arc-tunnel](image)

**Figure (3): Environment of twin arc-tunnel**

The overall excavation span and height of twin-arc tunnel are 23.5m (77.1 ft) and 10.1m (33.1 ft), respectively. Existing parallel tunnel beneath Yamalike twin-arc tunnel is a horse-shaped tunnel, with 10.25m (33.63ft) height and 7.04 m (23.09ft) width. Permanent lining of existing tunnels has already aged and rifted in many places. Therefore, vibration intensity must be strictly controlled as drilling and blasting are carried out in twin-arc tunnel. To ensure the safety and stability of existing tunnels, the safety criterion of the blasting vibration is assumed to be 5 cm/s (1.97 in/s) by referring to the Safety Regulations for Blasting of China (GB6722-2003) and some similar blasting cases (CQSEQ, 2004; Jiang et al., 2011; Nateghi et al., 2009; Jiang and Zhou, 2012).

The country rock of both twin-arc tunnel and existing tunnels is chiefly composed of marl with intercalation of sandstone, and its Protodyakonov coefficient $f$ equals 3~5. Because of serious weathering, the integrity of rock mass is poor and many fissures can be easily observed. The rock strata dip direction corresponds to the natural slope, and its strike direction intersects with the tunnel axis at small angles (about 0.05~0.12 rad). For the sake of construction safety and vibration control, both main tunnels of arc-twin tunnel are excavated in two steps; the upper bench of 48.8m$^2$ (525.3 ft$^2$) being excavated first and the lower bench of 33.9 m$^2$(364.9 ft$^2$) later, after the completion of middle drift and after the center wall has been concreted and formed.
Experiment Schemes and Vibration Measurement

Combined with the actual excavation situation of right main tunnel and the determination methods of key technical parameters in SV-cut mentioned above, the following blasting experiment schemes have been designed and implemented: (1) Scheme1, V-cut blasting, one shot-shaping of upper bench; (2) Scheme 2, SV-cut blasting, one shot-shaping of upper bench.

Figure 4 shows these two experiment schemes. As shown, the only differences between the two experiment schemes are: charge structure and ignition sequence of cut hole. Main blast parameters of V-cut and SV-cut are listed in Table 1 and Table 2, respectively. Due to that the existing parallel tunnels are still under operation, only one velocity monitoring point (3-component) was located on the haunch toward the blasting side of the right existing tunnel to monitor the lining vibration during blasting. Figure 5 shows the location of the monitoring point.
Figure (4): Blasting experiment schemes (unit: cm)

Table 1. Blast parameters of conventional V-cut blasting

<table>
<thead>
<tr>
<th>Borehole type</th>
<th>Number</th>
<th>Depth (m)</th>
<th>Length (m)</th>
<th>Charge per hole (kg)</th>
<th>Charge per delay (kg)</th>
<th>Detonation step no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuthole</td>
<td>8</td>
<td>2.4</td>
<td>2.78</td>
<td>1.8</td>
<td>14.4</td>
<td>1</td>
</tr>
<tr>
<td>Relief hole</td>
<td>8</td>
<td>2.2</td>
<td>2.28</td>
<td>1.4</td>
<td>11.2</td>
<td>5</td>
</tr>
<tr>
<td>Breast hole-I</td>
<td>10</td>
<td>2.2</td>
<td>2.28</td>
<td>1.2</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Breast hole-II</td>
<td>10</td>
<td>2.2</td>
<td>2.2</td>
<td>1.2</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Breast hole-III</td>
<td>12</td>
<td>2.2</td>
<td>2.2</td>
<td>1.2</td>
<td>14.4</td>
<td>11</td>
</tr>
<tr>
<td>Periphery hole</td>
<td>33</td>
<td>2.2</td>
<td>2.2</td>
<td>0.5</td>
<td>16.5</td>
<td>13</td>
</tr>
<tr>
<td>Bottom hole</td>
<td>8</td>
<td>2.2</td>
<td>2.2</td>
<td>1.2</td>
<td>9.6</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>89</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>90.1</td>
<td>—</td>
</tr>
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</table>

Table 2. Blast parameters of SV-cut blasting

<table>
<thead>
<tr>
<th>Borehole type</th>
<th>Number</th>
<th>Depth (m)</th>
<th>Length (m)</th>
<th>Charge per hole (kg)</th>
<th>Charge per delay (kg)</th>
<th>Detonation step no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuthole</td>
<td>8</td>
<td>2.4</td>
<td>2.78</td>
<td>1.4</td>
<td>6.4</td>
<td>1</td>
</tr>
<tr>
<td>Relief hole</td>
<td>8</td>
<td>2.2</td>
<td>2.28</td>
<td>1.4</td>
<td>4.8</td>
<td>3</td>
</tr>
<tr>
<td>Breast hole-I</td>
<td>10</td>
<td>2.2</td>
<td>2.28</td>
<td>1.2</td>
<td>11.2</td>
<td>5</td>
</tr>
<tr>
<td>Breast hole-II</td>
<td>10</td>
<td>2.2</td>
<td>2.2</td>
<td>1.2</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Breast hole III</td>
<td>12</td>
<td>2.2</td>
<td>2.2</td>
<td>1.2</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Periphery hole</td>
<td>33</td>
<td>2.2</td>
<td>2.2</td>
<td>0.5</td>
<td>14.4</td>
<td>11</td>
</tr>
<tr>
<td>Bottom hole</td>
<td>8</td>
<td>2.2</td>
<td>2.2</td>
<td>1.2</td>
<td>16.5</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td>89</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>86.9</td>
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</tbody>
</table>
Experimental Blast and Vibration Reduction Results

Both V-cut blasting method and SV-cut blasting method were carried out three times on site. From the field experiment results, the average advance per round of V-cut is 1.75m (5.74ft). The blasting efficiency of SV-cut is 8.5% higher than that of V-cut and the average advance per round increased to 1.9m (6.23 ft) with charging weight declined slightly.

Examples of monitored transverse velocity curves are given in Figure 6. During the process of V-cut blasting, the cutholes blast induced the most intensive vibration than other borehole types, and the value of PPV was 3.99cm/s (1.57 in/s). Because the distance between monitoring point and blasting source is not the shortest one, the largest PPV of lining might be bigger than or very close to 5cm/s (1.97 in/s). Nevertheless, during the process of SV-cut blasting, the outer and the inner deck of cuthole blasting-induced PPV values are only 1.66cm/s (0.65 in/s) and 0.97cm/s (0.38 in/s), respectively, which are much lower than the relief hole blast induced PPV value of 2.56cm/s (1.01 in/s). Cut blasting-induced PPVs of V-cut blasting and SV-cut blasting are listed in Table 2. It can be found that all PPV values in the three directions of cut blasting-induced PPV in SV-cut are obviously smaller than in V-cut. The average vibration reduction percentages of SV-cut are 43.2% in vertical direction, 68.6% in transverse direction and 30.7% in longitudinal direction, respectively.
Table 3. Vibration reduction ratios of SV-cut blasting

<table>
<thead>
<tr>
<th>Test No.</th>
<th>V-cut</th>
<th>SV-cut</th>
<th>Average vibration reduction ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>PPV (cm/s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>3.36</td>
<td>2.69</td>
<td>3.12</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>2.32</td>
<td>2.60</td>
<td>2.08</td>
</tr>
<tr>
<td>Horizontal</td>
<td>3.99</td>
<td>3.14</td>
<td>3.67</td>
</tr>
</tbody>
</table>

Conclusions and Future Work

Based on tunneling blasting engineering practices and millisecond blasting principle, this study introduced SV-cut (Stepped V-cut millisecond blasting method) and its main parameters’ determining methods. Field blasting experiments were carried out to verify the blast results and the vibration reduction effect of SV-cut. Analysis of SV-cut blasting process indicates that the application of interval charging structure and millisecond delay technology in cut holes could achieve both excellent blast results and vibration reduction effect. The performances of SV-cut and conventional V-cut are compared by field blasting experiments. The blasting efficiency of SV-cut is 8.5% higher than that of V-cut. Meanwhile, cut blasting-induced PPV is reduced by at least 30%.

Until now, the rock fragmentation and vibration reduction mechanisms for SV-cut are not fully understood and should be researched further to the end of optimizing and guiding the tunnel blasting process.

REFERENCES
